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Stratigraphy regional correlation and depositional environment of the Bonner Formation (Precambrian Missoula group southwest Montana)

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STRATIGRAPHY, REGIONAL CORRELATION
AND DEPOSITIONAL ENVIRONMENT
OF THE BONNER FORMATION
(Precambrian Missoula Group, Southwest Montana)

by

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ABSTRACT

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Stratigraphy, Regional Correlation, and Depositional Environment of the Bonner Formation (Precambrian Missoula Group, Southwest Montana)

Director: Donald Winston

Three units within the Bonner Formation in southwest Montana can be correlated from sections at Wise River, Copper Creek, Emerine Lookout, and Flint Creek Hill. The lowermost unit (unit 1) at Wise River is uniformly medium to coarse-grained quartzite, but in the other sections it is composed of fining-upward quartzite packages. Characteristic packages of the Bonner contain medium to coarse-grained, high-angle cross-bedded to horizontally laminated quartzite in their lower and middle parts overlain by medium to fine-grained, ripple cross-bedded and horizontally laminated quartzite in their upper parts. Unit 2 is uniquely coarser grained than any other parts of the sections. At Wise River unit 2 contains gravel lenses up to 90cm thick interbedded with medium to coarse-grained quartzite. Unit 2 at Copper Creek contains medium to coarse-grained quartzite with interbedded conglomerate lenses up to 30cm thick. Further north at Emerine Lookout and Flint Creek Hill, gravel lenses as thick as 20cm occur in fining-upward quartzite packages which are medium to fine-grained in their upper parts. Unit 3 of each section lacks conglomerate and is composed of fining-upward quartzite packages 30cm to 5.6m thick which are medium to coarse-grained in their lower and middle parts and medium to fine-grained in their upper parts. In the upper part of the Emerine Lookout section, approximately one third of the packages contain siltite in their upper parts.

Correlation of the four sections is based primarily on the presence of the conglomeratic interval (unit 2), which is uniquely coarser grained than any other parts of the Missoula Group. The other units are correlated on the basis of stratigraphic position with respect to unit 2, and similarity of lithology, sedimentary structures, and bedding characteristics. Thus, the Bonner Formation in southwest Montana is defined as the predominantly medium to coarse to pebbly quartzite unit.

The fining-upward rock packages which dominate the Bonner Formation represent channel-fill deposits formed by vertical aggradation during waning discharge, flow velocity, and depth in low-sinuosity braided stream channels with very high width/depth ratios, which crossed the middle and upper reaches of ancient alluvial fans. The conglomeratic interval represents an extensive "gravel sheet" which temporarily advanced downslope as the alluvial fan system prograded northward. Progradation may have resulted from uplift of the source area or from increased precipitation and stream discharge rates.

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INTRODUCTION

Stratigraphic Setting

During the period from about 1,450 to 850 million years ago, sediments accumulated in a broad, slowly sinking basin which trended northwest to southeast across much of present-day western Montana, northern Idaho, eastern Washington, and adjacent southern Canada (Fig. 1). The resulting package of rock, now known as the Belt Supergroup, reaches an astounding thickness of greater than 20 kilometers (67,000 feet) near Alberton, Montana (Harrison, 1972) (see Figs. 1 and 2). The main subdivisions of the Belt Supergroup are, (in ascending order), the Prichard Formation, the Ravalli Group, the Middle Belt Carbonate, and the Missoula Group. Clapp and Deiss (1931) originanly named the Missoula Group, and reported a thickness of approximately 5,485 meters (18,000 feet) near Missoula, Montana. Gradational contacts separate all seven Missoula Group formations which, in order of decreasing age, are the Snowslip, the Shepard, the Mount Shields, the Bonner, the McNamara, the Garnet Range, and the Pilcher.

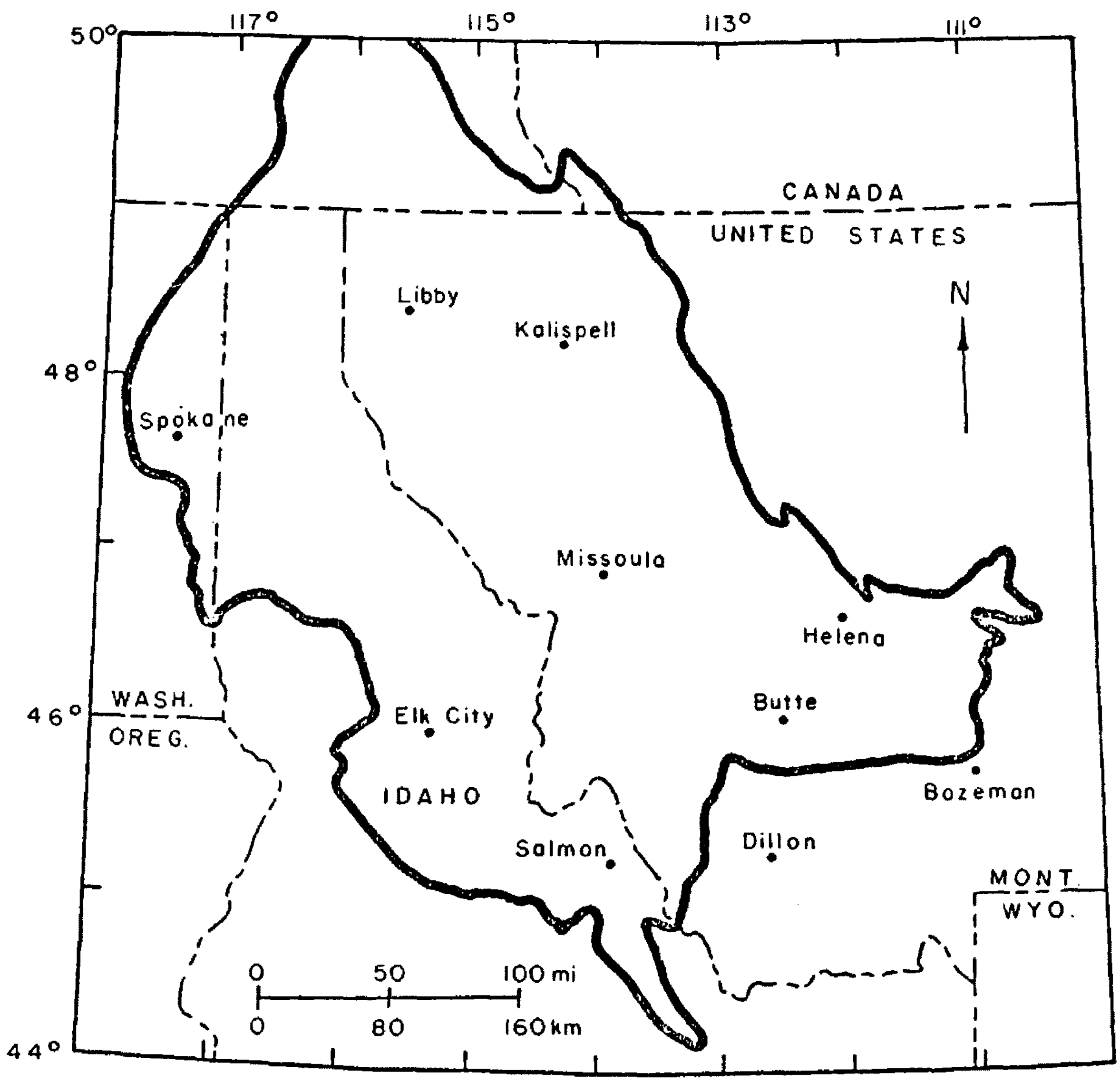


Figure 1. Index map showing location and extent of Precambrian Belt basin (modified after Harrison, 1972).

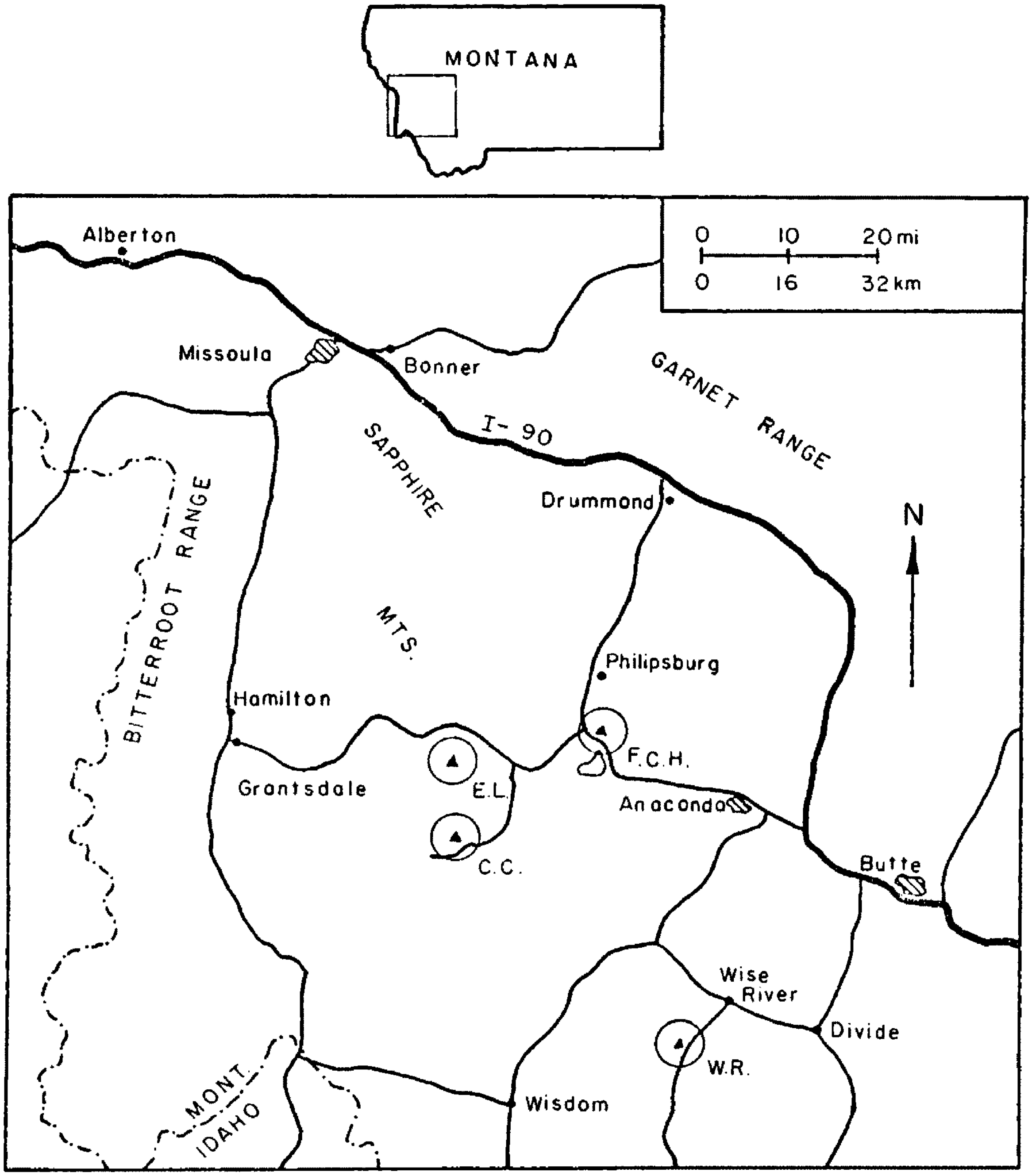


Figure 2. Index map to study area showing location of measured sections (▲).

At the type locality along the Blackfoot River north of the town of Bonner (Fig. 2), an approximately 300 meter (1,000 foot) thick section (Winston, oral communication; 1978) of predominantly pinkish colored, medium to coarse-grained, cross-bedded, feldspathic quartzite represents the Bonner Formation. In northwestern Montana the Bonner is dominated by medium to fine-grained, horizontally laminated quartzite, and in the southwestern part of the state (this study), the lower half of the formation contains interbedded gravel lenses with pebble and cobble size increasing southward. The underlying Mount Shields Formation (mixed siltite-argillite and quartzite) differs from the Bonner in that: a) the quartzite units are relatively finer-grained (predominantly medium to very fine sand), b) they commonly occur as flat and even, horizontally laminated beds, and c) the Mount Shields contains thick intervals of red argillite. Red and green siltite and argillite (slightly metamorphosed siltstone and claystone respectively) of the McNamara formation overlies the Bonner in central-western Montana. To the south, the McNamara contains interbedded quartzite which, at the base of the formation, is finer grained than the adjacent Bonner quartzite.

Location of Study

Four stratigraphic sections were measured, described, and sampled in part of southwestern Montana (Fig. 2). Three of these occur in Granite County, and the fourth is located in northern Beaverhead County. Appendix I provides detailed information concerning section locations and access. The four sections are herein referred to as Wise River, Copper

Creek, Emerine Lookout, and Flint Creek Hill. At Wise River and Copper Creek, resistant quartzite cliffs outcrop in the middle third of sloping, rock-covered mountainsides. Carving by high-mountain glaciers resulted in the steep, good exposure at Emerine Lookout, while the Flint Creek Hill outcrops are in roadcuts.

Tectonic Setting

All four stratigraphic sections occur within Laramide thrust plates which moved eastward from the area now occupied by the Idaho Batholith during late Cretaceous time (about 75 m.y. ago). The three northern sections, Flint Creek Hill, Emerine Lookout, and Copper Creek, lie on the Sapphire block (Hyndman, oral communication, 1980), displaced approximately 60km (37 miles) eastward (Hyndman, 1980). The section at Wise River is part of the Pioneer block (Hyndman, oral communication, 1980) which has probably moved a comparable distance eastward (Winston, oral communication, 1980). Therefore, the present geographic distribution of the sections closely resembles their spatial relationship during deposition. Consideration of sediment source area must include restoration of the thrust plates to their original positions 60km to the west.

Previous Geologic Work

Early work involving Missoula Group rocks in the region covered by this study was done by both Moore (1956), who described outcrops of Hellgate and conglomeratic McNamara approximately ten miles northeast of my Wise River section, and Noel (1956), who worked about twenty miles north of Wise River and there described the Miller Peak and Hellgate formations (see Fig. 13). Poulter (1957) originally published detailed work on the Belt section at Flint Creek Hill, and more recently, Hughes (1970) described the Miller Peak, Bonner, McNamara, and Garnet Range formations approximately twenty miles northwest of Flint Creek Hill. Calbeck (1975) measured the Wise River section, correlated it with the Missoula Group, and interpreted the sands and gravels as braided stream deposits. The area in which my Copper Creek section occurs was studied by Pederson (1976), who assigned the quartz-pebble conglomerate to the Bonner. A facies tract (depositional) model (Fig. 3) has been developed for the Belt strata by Winston (1972, 1973a, 1973b, 1977, 1978). In this model, which incorporates data from the Flint Creek Hill and Wise River sections, he interprets the Missoula Group as a braided stream and sea margin sequence, and correlates the Wise River section as the coarsest facies of the Bonner.

Extensive work involving tectonic features, geometry, and stratigraphy of the Belt basin in the region northwest of the present study area has been published by Harrison and Campbell (1963), Harrison and Jobin (1963), Harrison (1972), and Harrison, Griggs, and Wells (1974). Obradovich and Peterman (1968) provide radiometric age dates from the Belt rocks.

Purpose of Study

Some of the correlations which support the proposed depositional model (Winston, 1977, 1978) for the Missoula Group were previously undocumented (Harrison, 1973) in southwestern Montana. Other stratigraphic problems became apparent in September, 1978, when I learned that

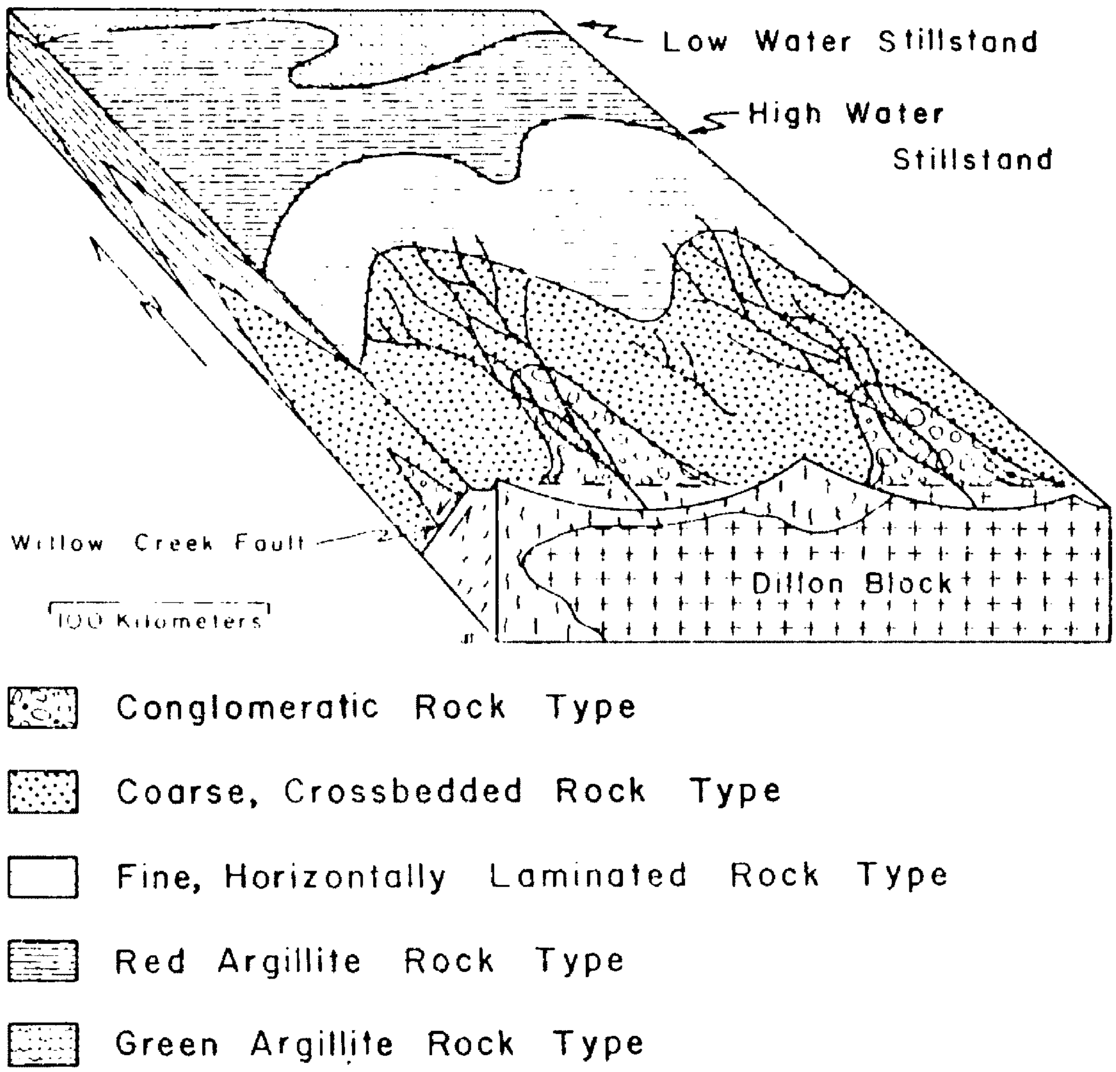


Figure 3. Schematic block diagram of Winston's (1978) fluvial facies model showing braided streams flowing from the Dillon Block northward to the "Belt Sea".

Chester Wallace (U.S. Geological Survey) maps what I believe to be Bonner Formation as lower Mount Shields Formation in many parts of southwestern Montana including Wise River and Flint Creek Hill. The principal goals of this study are as follows: 1) to provide detailed stratigraphic data on the Bonner Formation, 2) to establish a regional correlation for the Bonner in part of southwest Montana, and 3) to interpret the environment of deposition on both a local and regional scale. Accomplishment of these goals will hopefully clarify the picture of Missoula Group stratigraphy in this area.

Methods of Study

The summers of 1978 and 1979 were spent working in the field. At each section, I began by measuring the entire thickness using a Jacob staff and Brunton compass. While doing this, the rock was marked at ten-foot intervals and numbered every twenty feet with silver spray paint. I then described the section in detail by sketching the outcrop profile and recording vertical and lateral variations in sedimentary structures, grain size, grain shape, sorting, bedding thickness, geometry of sedimentation units, and color (Appendix II). Representative samples were studied in thin section to determine more accurately texture and mineralogy. Staining of rock chips with Sodium Cobaltinitrite saturated solution allowed determination of potassium feldspar percentages, and I used X-ray diffraction techniques to determine clay mineralogy of the quartzite matrix and siltite-argillite beds.

General Characteristics of Braided Rivers

An understanding of the characteristics of modern braided rivers is our most useful tool in interpreting ancient braided stream deposits. Modern braided rivers are characterized by several or many relatively low-sinuosity channels with bars and small islands (Miall, 1977). The channels commonly have high (greater than 40) width/depth ratios, and their floors may be covered with any or all of the following bedforms: longitudinal, transverse, and linguoid bars, dunes, ripples, plane beds, scour hollows, and lag gravels. Though some braided rivers flow perennially, most are characterized by ephemeral, often flashy discharge. Sediment load is generally high. Several rivers described by Miall (1977) have flood velocities ranging from 2.4 to 6 meters per second and flood discharges ranging from 600 to 40,000 cubic meters per second. During periods of waning flow, higher relief structures such as bars may be eroded or dissected and smaller-scale structures may be superimposed on the larger bedforms. Several recent studies have shown that accumulation of significant thicknesses of sediment by vertical accretion processes is particularly characteristic of braided rivers (Miall, 1977). Within these accumulations, there is little argillaceous sediment of overbank origin preserved, and individual sediment units are lenticular (Allen, 1965b). Williams and Rust (1969) demonstrated that vertical aggradation in channels of the Donjek River results in fining-upward depositional cycles whose thicknesses depend on channel depth. For a thorough review of the braided river depositional environment refer to Miall (1977).

CHAPTER II

TEXTURE, MINERALOGY, AND COLOR

Texture and Mineralogy

Most of the Bonner Formation consists of moderately to moderately well sorted, medium to coarse-grained (average 0.55mm) feldspathic quartzite, which generally contains 87 to 96% quartz, up to 12% orthoclase (with slight to moderate sericite alteration), and trace to 2% of both microcline and plagioclase. Most quartz grains are subangular to well rounded, while the feldspar is angular to well rounded. This relationship between grain roundness suggests contribution from more than one source area. Up to 2% sericite matrix and 8% silica cement sometimes occur in the rock. Traces of muscovite, tourmaline, zircon, and hematite are also present.

Where the quartzite becomes conglomeratic, compact to elongate granules, pebbles, and cobbles, which reach a maximum diameter of 10cm (4 inches) at Wise River, occur as closely-packed but predominantly matrix-supported concentrations. Both the medium to coarse sand matrix, and the pebbles are moderately to poorly sorted, and most elongate clasts are aligned more or less parallel to bedding. The mineralogy of the medium to coarse-grained quartzite does not differ significantly from that of the conglomerate. Subrounded to well rounded quartz and quartzite clasts dominate the large pebble and cobble fraction, whereas the granule to medium pebble fraction also contains common angular to well rounded orthoclase and microcline, and minor chert, jasper and argillite. In general, increase in roundness of the gravel accompanies an increase in grain size. Such a relationship between roundness and size is common in natural sand or gravel (Pettijohn, 1957). The color of the clasts, in order of decreasing abundance, is as follows: quartzite - red to purple, light to dark gray, milky, pink; quartz - milky, gray, clear; potassium feldspar - white, rare pink; chert - black, brown; jasper - red; argillite - purplish gray.

The amount of orthoclase, muscovite, and sericite matrix in the medium to fine-grained quartzites of the Bonner increases at the expense of quartz. These quartzites are commonly composed of 38 to 88% quartz, up to 50% sericite matrix, as much as 28% orthoclase, trace to 3% muscovite, and trace to 2% of both microcline and plagioclase. Medium to fine-grained quartzite (average 0.27mm) varies from poorly to well sorted, with angular to rounded quartz and angular to well rounded feldspar. Where fine to very fine-grained (average 0.15mm), the rock is predominantly moderately well to well sorted, with angular to subrounded quartz and angular to well rounded feldspar. Muscovite, which occurs in the finer sands as detrital flakes up to 4mm lying along bedding planes, increases in abundance with decrease in sand grain size. The thin flakes settle out with finer-grained sands because of their platy shape.

Argillite of the Bonner Formation consists of clay-sized detrital muscovite. Larger flakes of muscovite lie along the flat, millimeter-scale bedding planes of the rock. Mud cracks are notably absent in these argillites.

In all of the quartzite and conglomerate, most quartz exists as single grains with straight to slightly undulose extinction. Lesser amounts of strongly undulose single grains, semicomposite, composite, and composite metamorphic grains (Folk, 1974, p. 73) are also present. These grain types suggest igneous and metamorphic source rock (Folk, 1974). In the majority of the rock, orangish-brown hematite coats the grains.

Color

Purplish gray to medium gray shades dominate the rock. Less common colors, in order of decreasing abundance, include grayish purple, whitish, pinkish gray, and purplish pink. Gray colors occur most often in medium to fine-grained quartzite.

As suggested for rocks of the Difunta Group (McBride, 1974), the purple and pink colors in the Bonner result from pervasive hematite grain coatings. Whitish and gray colors most likely reflect an absence of hemtatite and possible presence of chlorite.

CHAPTER III

SECTION DESCRIPTIONS AND INTERPRETATIONS

Definition of Terminology

In all section descriptions, the terms "parting" and "parted units" are occasionally used. In this report, "parting" refers to planes of separation parallel to layering or bedding in the rock, and "parted units" are simply sheet-like intervals of rock bounded by parting planes. Appendix III provides detailed information concerning scale and geometry of parted units.

Wise River Section

Description. The 148 meter (490 foot) Wise River section can be divided into three distinct units (for detailed description see Appendix II).

The lowermost unit (0-22 meters) consist of uniformly medium to coarse-grained quartzite parted on a scale of 50cm to 1.8m. Some parted units show low-amplitude (less than 15cm) scour at their bases. Most of the quartzite reveals no internal structure, but occasional trough cross-bedding (Fig. 4) up to 15cm thick and low-angle cross-bedding (Fig. 5) up to 8cm thick can be seen. Horizontal laminae up to 10cm thick are rare. At approximately 6.5m, a pebble lens 7cm thick by 1.7m long occurs at the top of a 45cm thick quartzite bed. It is overlain by two medium to fine-grained, planar cross-bedded quartzite lenses 2.5cm by 18cm which

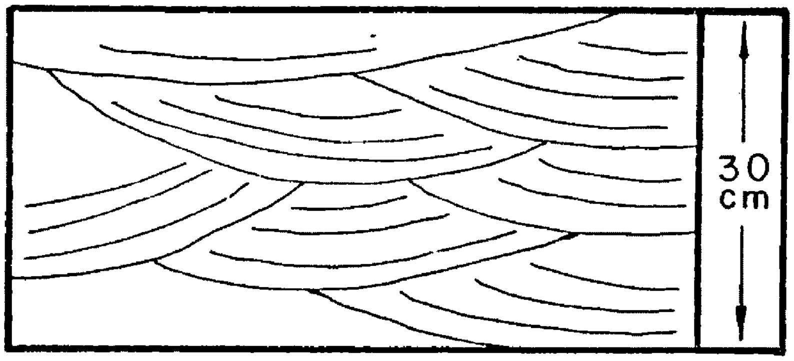


Figure 4. Sketch of trough cross-bedding in medium to coarse-grained quartzite.

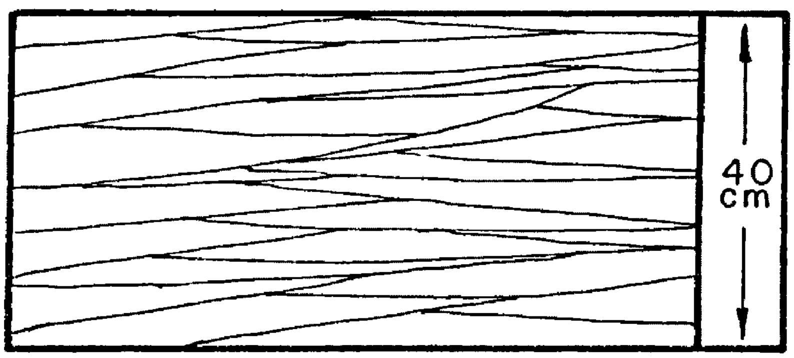


Figure 5. Sketch of low-angle cross-bedding in medium to coarse-grained quartzite.

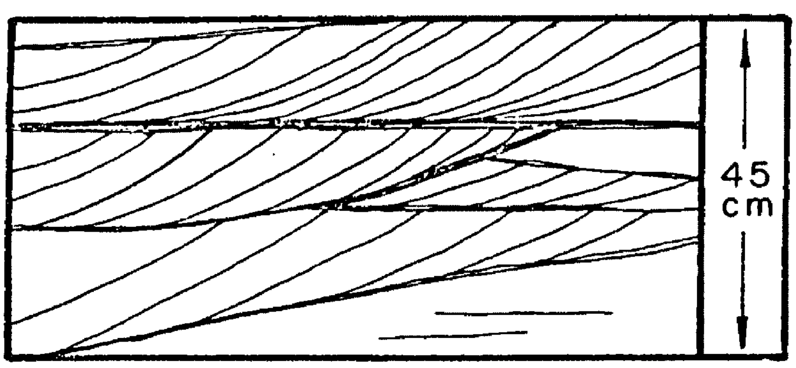


Figure 6. Sketch of planar cross-bedding in medium to coarse-grained quartzite.

are in turn erosionally overlain by medium to coarse-grained quartzite. The remainder of this lower unit contains only rare isolated pebbles up to 2.5cm which become slightly more abundant in the top meter.

Interbeds of conglomerate and medium to coarse-grained quartzite comprise the second unit (22-40 meters). The upper two thirds of the unit are mostly medium to coarse-grained quartzite, while conglomerate dominates the lower third. Its base is marked by the abrupt appearance of closely-packed, predominantly matrix supported gravel with clasts up to 10cm in diameter, but mostly less than 7cm. For a more detailed description of the conglomerate see Chapter II. The lower half of unit two is characterized by relatively coarse conglomerate in horizontal lenses up to 90cm thick and greater than 20m wide separated by intervals of medium to very coarse-grained quartzite up to one meter thick. Parting is on a scale of about 5m. The conglomerate lenses show no internal structure except for a general horizontal alignment of elongate pebbles. Some quartzite interbeds display low angle cross-bedding not more than 6cm thick. The pebble beds become thinner and more lenticular upward decreasing to 2.5cm thick by 50cm long near the top of the unit. As the pebble beds become smaller, the pebbles within the beds also decrease in size. The upper half of unit 2 contains very few pebbles larger than 2cm, and the non-conglomeratic, medium to coarse-grained quartzite shows abundant trough cross-bedding up to 15cm thick, smaller low-angle cross-bedding, and minor planar cross-bedding as thick as 7cm. The scale of parting here ranges from 60cm to 1.8m. The top two meters are medium-grained quartzite with few pebbles and minor trough and planar cross-bedding up to 8cm thick in the lower half and ripple cross-bedding (less than 6cm thick) in the upper half.

The upper unit (40-148 meters) is composed of fifty-six fining-upward rock packages that range in thickness from 30cm to 5.6m and average 1.9m. The most common packages contain relatively thick intervals of medium to coarse-grained, predominantly low-angle (maximum 15cm thick) or trough (maximum 20cm thick) cross-bedded quartzite in their lower parts overlain by medium, medium to fine, or fine-grained, predominantly ripple cross-bedded (maximum 6cm thick) or horizontally laminated (maximum 5cm thick) quartzite in their upper parts. Flat and horizontal parting planes with little or no relief commonly mark the bases of the packages. Lenses of small pebbles are restricted to the lower parts of the bottom three packages. Second in abundance are packages with lower intervals of medium-grained quartzite containing abundant ripple (less than 6cm thick) cross-bedding and lesser trough (maximum 20cm thick) cross-bedding and horizontal lamination (maximum 8cm thick). In these packages, the lower intervals are overlain by relatively thin intervals of horizontally (up to 4cm) laminated siltite or silty fine-grained quartzite. Only rare packages span the complete fining-upward sequence of coarse to medium to fine sand to silt. In most packages, one or more components of the sequence are absent. Although most packages fine upward, a few are reversely graded passing upward from medium grained to coarse-grained quartzite in their bottom parts. In others, coarser material alternates with finer. The scale of parting within packages commonly decreases upward corresponding to the decrease in grain size. Most parted units are tabular with very high width to thickness ratios.

Depositional Environment. Of the four sections studied, Wise River is the southernmost and contains the coarsest gravel and the largest conglomerate lenses. It is, therefore, probably closest to the original source area.

In his recent review, Cotter (1978) found that virtually all pre-Silurian rivers were braided. Their braided pattern most likely resulted from the absence of vegetation during that time. The quartzite in the lowermost part (0-22 meters) of the Wise River section probably represent channel deposits in very broad, rather flat-bottomed braided channels. The absence of fine-grained material and the occasional scoured surfaces reflect the relatively high energy of the depositing streams and the periodic reworking of sediments during successive flood events. Trough cross-bedding is common in Precambrian (Eriksson, 1978; Selley, 1965) to modern (Smith, 1970; Williams, 1971) braided fluvial deposits. As in these deposits, the trough cross-bedding in unit 1 formed as sinuous crested ripples and dunes migrated downstream along the channel bottoms in the lower flow regime. The occasional low-angle cross-beds (washed-out ripples and dunes or antidunes) and the rare horizontally laminated beds indicate periodic shifts to transitional and upper regime. The abundant structureless quartzite is interpreted as upper flow regime plane bed deposits which appear uniform due to the homogeneity of the sand. The small pebble lens represents channel lag gravel over which straight-crested sand waves (Blatt and others, 1980) or transverse bars in the lower flow regime migrated during waning flood stages, depositing the medium to fine-grained, planar cross-bedded sand. Subsequent erosion, probably during rising or high stage of the next flood event, scoured away all the medium to fine sand except for the two small lenses.

The coarse-grained, lenticular, horizontally oriented conglomerate lenses which dominate the lower third of unit 2 (22-40 meters) probably represent longitudinal gravel bars deposited in the upper flow regime in very high-energy braided channels. These bars, with their horizontally oriented elongate pebbles, were possibly similar to longitudinal bars in the Platt River described by Smith (1970) which show a crude horizontal internal stratification. Low-angle cross-bedding in some quartzite interbeds probably indicates upper to transitional flow regime in some sandy parts of channel floors. The presence of more competent channels may indicate increased discharge rates or northward advance of a more proximal facies. In the upper half of unit 2, the relatively small pebble size and the presence of trough and planar cross-bedding in the non-conglomeratic quartzite reflect a decrease in stream power and a change from predominantly upper to predominantly lower flow regime conditions. Planar cross-bedding in braided stream sediments is commonly attributed to deposition by migrating transverse bars (Smith, 1970; Williams, 1971; Rust, 1972) or straight-crested dunes (Selley, 1965; Allen, 1964a). Small conglomerate lenses in the upper part of unit 2 resemble channel lag deposits described by Allen (1965b, p. 129). Deposition of medium-grained sand at the top of the unit, showing an upward decrease in scale of cross-bedding, indicates lower flow regime conditions and further reduction in stream depth, velocity, and sediment transporting ability (Simons and Richardson, 1961). The direct correspondence between thickness of parted units and sediment grain size suggests that the scale of parting decreases along with channel size. Thus, the lower half of unit 2 was deposited in relatively deep and wide braided channels dominated by upper regime flow. The gradual upward changes in the rock reflect the development of shallower and narrower channels with less discharge dominated by lower flow regime conditions in the upper half of the unit.

The fining-upward rock packages of unit 3 (Fig. 7) are in many ways similar to upward-fining depositional cycles described by Eriksson (1978) in cross-bedded sandstones of the Archaean Moodies Group. In both deposits, relatively thick intervals ofpredominantly trough cross-bedded, coarse to medium-grained sand capped by thin layers of ripple cross-bedded or horizontally laminated, finer-grained sand and/or minor silt are very common. Upward fining fluvial cycles form by channel-filling either through vertical aggradation or through lateral point bar accretion (Eriksson, 1978). Differentiating high-sinuosity stream deposits characterized by lateral point bar accretion from deposits of low-sinuosity streams characterized by vertical aggradation is particularly difficult in sequences with little or no mudrocks (Long, 1978) because abundant overbank mudstone

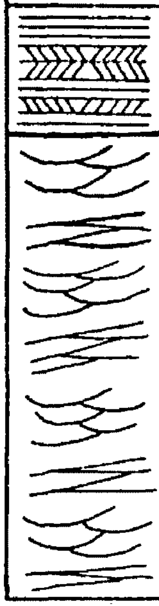
	DESCRIPTION	INTERPRETATION
	med - fine, ripple cross-bedded and horizontally laminated quartzite	channel-fill sands deposited from upper and lower regime flow during low discharge
	med - crs, low-angle and trough cross-bedded quartzite	channel-fill sands deposited from sinuous-crested and washed out ripples and dunes during relatively high discharge

Figure 7. Typical fining-upward quartzite package very common in all four measured sections.

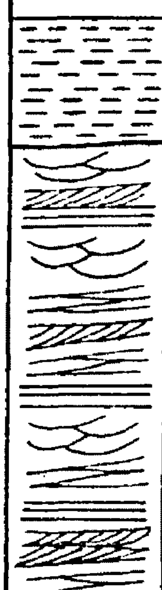
	DESCRIPTION	INTERPRETATION
	siltite or fine sandy siltite, horizontally laminated less than 1cm	suspended load deposits formed in abandoned channels or from overbank flooding
	med - crs, planar, trough, and low-angle cross-bedded and horizontally laminated quartzite	channel-fill sands deposited from upper and lower regime flow during relatively high discharge

Figure 8. Fining-upward package formed by combination of bed load and suspended load deposition. Generally restricted to upper part (unit 4) of Emerine Lookout section.

is probably the most diagnostic feature of high-sinuosity streams. However, Williams (1966) has shown that lateral migration of shallow streams may result in the formation of large-scale planar cross-stratification. This large-scale planar cross-stratification forms on the point bars as they accrete laterally, and has been termed epsilon cross-stratification by Allen (1963b). This process has also been documented by Moody-Stuart (1966), who suggests that the absence of large-scale epsilon cross-stratified units which decrease in grain size upward may indicate deposition by low sinuosity streams in which lateral point bar accretion does not occur. The rock packages of unit 3 fine upward in the sense that a thick lower interval of relatively coarse sand is rather abruptly overlain by a relatively thin upper interval of finer sand and/or mud. The packages commonly do not gradually fine upward. Packages also lack epsilon cross-stratification. Based on the lack of evidence for point bar and overbank deposition, fining-upward packages in unit 3 of the Wise River section are interpreted as channel-fill deposits formed by vertical aggradation within low-sinuosity braided stream channels. This interpretation closely corresponds to that proposed by Eriksson (1978) for the upward-fining cycles in the Moodies Group. The trough and low-angle cross-bedded, coarse to medium-grained quartzite comprising the lower and middle parts of packages reflects migration of sinuous-crested dunes, washed-out dines, and possibly antidunes along the channel bottoms during periods of more rapid and deeper stream flow. Ripple cross-bedded and horizontally laminated, medium to fine-grained quarzite in the upper parts of packages represent channel-filling under lower and upper flow regime conditions during relatively slow, shallow flow. The minor horizontally laminated silts probably formed by accumulation of suspended material from nearly standing water in abandoned channels and/or overbank flow into such channels. Thus, each fining-upward package resulted from deposition during periods of waning discharge as flow depth and velocity gradually declined. The large range in package thicknesses probably reflects a high variability in size of channels on the alluvial plain. Alternation of coarse and fine material within some packages suggests that during the deposition of these packages stream power fluctuated rather than decreased steadily. The few packages with reversely graded lower part simply deposition during an increase in stream competence.

Copper Creek Section

Description. The 130 meter (430 foot) Copper Creek section consists of three definable units. Salient characteristics are presented here, and Appendix II provides more detailed information.

Unit 1 (0-20 meters) contains nine fining-upward packages which range from 50cm to 4.5m thick and average 1.8m. Medium to coarse, coarse, or medium to very coarse-grained, planar (up to 20cm thick), trough (up to

10cm thick), or low-angle (up to 3cm thick) cross-bedded quartzite comprises the bulk of each package. The upper parts are composed of tabular or lenticular beds of medium to fine, fine, or silty fine-grained quartzite showing horizontal lamination and less common small ripple cross-bedding up to 3cm thick. The top two fining-upward sequences of unit 1 contain gravel lenses within their lower, coarser parts with pebbles up to 2.5 cm in diameter. Tabular to lenticular parted units generally thin upwards from a maximum of 1.9m at the bases of packages to 25cm or less in the upper, fine-grained parts.

The middle interval (20-38 meters) is characterized by relatively coarse-grained or conglomeratic quartzite parted on a large scale, and lacks fining-upward packages. Most tabular parted units are 1.1m to 3m thick and consist of medium to very coarse-grained quartzite with interbedded lenses of matrix-supported conglomerate. The pebble lenses are coarsest and thickest near the middle of the interval where the quartz and quartzite pebbles reach 7cm in diameter and occur in lenses up to 30cm thick and 15m wide. Throughout unit 2, however, most pebbles are not larger than 4cm. The lenticular, poorly sorted pebble concentrations commonly parallel layering in the outcrop, but lack internal structure. Broad and flat layers of gravel only a few pebbles thick are rare. Quartzite intervals up to 3m thick separate lenses of conglomerate. In the few zones not covered with lichen, this quartzite displays horizontal lamination and low-angle cross-bedding up to 5cm thick.

Loose rock debris obscures nearly half of the upper unit (38-130 meters). About two-thirds of the exposed portion, however, is composed of twenty fining-upward packages averaging 1.5m thick and containing one or two parted units each. Package bases are generally marked by flat, horizontal parting planes. Packages commonly have a lower interval of medium to coarse grained, predominantly trough (maximum 20cm thick) or low-angle (maximum 8cm thick) cross-bedded or horizontally laminated (maximum 5cm thick) quartzite overlain by an upper interval of medium to fine-grained, horizontally laminated (maximum 3cm thick) or ripple cross-bedded quartzite in lenses or tabular beds not thicker than 30cm. Rare packages grade upward to siltite. The lower parts of some packages contain "floating" angular mud clasts as large as 2.5cm by 10cm. Reverse grading in the bottom parts, and alternation of coarser and finer material within packages are rare. Several packages are capped by scoured or load-casted surfaces with amplitudes less than 15cm, and the upper bedding surface of some shows irregular, discontinuous-crested current ripples up to 3cm high. A few medium to fine-grained talus blocks in the upper thirty meters of the section also have surfaces marked by straight-crested, symmetrical ripples with wavelengths of 5cm to 8cm. The remaining third of unit 3 is composed of four intervals of uniform, medium to coarse-grained quartzite 2m to 5.4m thick. These intervals, which contain two, three, or four tabular parted units of 1.1m average thickness, occasionally interrupt the normal succession of fining-upward packages. Sedimentary structures within these intervals include trough (maximum 20cm thick) and low-angle (maximum 3cm thick) cross-bedding and horizontal (maximum 3cm thick) lamination. Angular mud clasts up to 2cm by 8cm, with long axes generally parallel to parting planes, occur in one of these intervals.

Depositional Environment. Fining-upward packages in the lower unit (0-22 meters) probably formed as a result of vertical aggradation in braided channels whose depths may have ranged from 50cm to 2m or more. The coarser, planar, trough, and low-angle cross-bedded sands were deposited primarily during lower regime flow, but occasionally, lower regime bedforms were scoured out duirng transitional or upper regime flow resulting in low-angle cross-bedding. As discharge, velocity and stream competence decreased, the upper, finer-grained sediments of each package accumulated under both lower and upper regime flow. The common lenticular shape of the relatively fine-grained, top parted units probably reflects deposition in small and shallow remnant channels left as water level dropped. Gravel lenses near the top of unit 1 indicate an increase in stream competence.

The relatively coarse sediments and thick, tabular parted units of the middle interval represent deposition in wider and deeper braided streams. Miall (1977) describes several modern braided streams with bankfull width/depth ratios ranging from 100 to 150. Assuming similar width/depth ratios for the channels in which unit 2 accumulated, and a depth of three meters or more, these channels would have been up to 450m or more wide. Flow was almost entirely in the upper regime as longitudinal gravel bars migrated down the sandy-bottomed channels (e.g. Williams and Rust, 1969). In a few places, thin sheet-like accumulations of lag gravel must have mantled the flat channel bottoms (e.g. Allen, 1965b).

Fining-upward sandy packages in the upper unit (38-130 meters) demonstrate the return of lower-energy (less competent) braided channels whose beds aggraded vertically possibly from periods of highest through waning flow, under both upper and lower flow regimes. Silt beds were rarely preserved at the tops of packages, and were probably more commonly scoured away during subsequent rapid flows with bits and pieces deposited as mud clasts in the coarser parts of the overlying packages. During waning low-stage flow, small current ripples migrated along the bottoms of some channels. Relatively small channels were sometimes cut off from active channels during low-stage flow as described by Doeglas (1962) in the Durance River forming small channel ponds. The small, straight-crested symmetrical ripples could have formed as wind-generated waves moved across the surfaces of these ponds. The intervals of uniform, medium to coarse-grained quartzite are virtually identical to the lower and middle parts of the fining-upward packages, and they probably represent stacked partial packages whose finer upper parts have been scoured away. Mud clasts in one of the intervals attest to the erosion of silty mud which caps some packages. The apparent absence of marked, undulating erosion surfaces may be due to flat sheet erosion during rising flood stage as described by Long (1978), or to a very high sediment bedload which prevented erosion altogether. In any case, it appears that increasing discharge did not cut well defined channels.

Emerine Lookout Section

Description. The 243 meter (800-foot) Emerine Lookout section is described in four units. Refer to Appendix II for more detail.

The lowest unit of the section (0-62 meters) is composed of twenty-five fining-upward quartzite packages ranging from 45cm to 5m thick, averaging 2m. The lower and middle parts of most packages are typically tabular intervals of medium to coarse-grained, planar and trough (up to 30cm thick) cross-bedded, low-angle (up to 10cm thick) cross-bedded and/or horizontally (up to 10cm thick) laminated quartzite. Some coarse-grained beds contain scattered angular mud clasts. Medium to fine-grained quartzite showing horizontal lamination up to 10cm thick and/or ripple cross-bedding up to 6cm thick commonly forms the upper parts of the packages. These relatively fine-grained upper parts vary in geometry from lenses 8cm thick and 1.6m wide to tabular, even beds up to 20cm thick which extend at least 5m along the outcrop. The tops of some packages are scoured by the overlying coarse quartzite beds.

Nine fining-upward rock pacakges ranging from 70cm to 4.8m thick comprise the second unit (62-84 meters) of the section. Packages typically contain medium to coarse-grained, partially conglomeratic, trough (maximum 25cm thick), planar (maximum 60cm thick), and low-angle (maximum 10cm thick) cross-bedded and minor horizontally (maximum 10cm thick) laminated quartzite in their lower and middle parts. Angular mud clasts up to 8cm long occur in some of these relatively coarse intervals, and some have scoured (amplitude less than 15cm) basal surfaces. Nearly all packages contain up to 15% interbedded conglomerate lenses with pebbles generally not greater than 2cm in diameter. The largest gravel lenses, which occur mostly at the tops of parted units, are 15cm thick and 12m long. In these lenses, a few pebbles reach 4cm in diameter. Though most of the conglomerate lacks internal structure, some displays minor low-angle cross-bedding up to 5cm thick. The upper parts of the packages are composed of tabular or lenticular intervals of medium to fine-grained or silty fine-grained, horizontally laminated or small ripple cross-bedded (up to 2cm thick) quartzite which do not exceed 45cm in thickness. Parted units generally thin upward from a maximum of 2m at the bottoms of packages to 20cm or less at their tops.

The third unit of the section (84-119 meters) consists of twenty fining-upward packages ranging from 45cm to 4.4m thick. The most abundant packages contain relatively thick intervals of medium to coarse-grained, planar (up to 25cm thick), trough (up to 8cm thick), and/or low-angle (up to 15cm thick) cross-bedded and horizontally (up to 7cm thick) laminated quartzite overlain by thinner intervals of medium to fine-grained, horizontally laminated and ripple (up to 4cm thick) cross-bedded quartzite. Some packages are similar to these except that the upper medium to fine-grained quartzite passes upward to thinner (10-20cm) intervals of thinly laminated, silty fine-grained quartzite or siltite. Many of the lower, coarser parts of packages contain scattered angular mud clasts up to 2cm by 10cm, and a few have scoured bases. Rare isolated quartzite and quartz pebbles occur within medium to coarse-grained quartzite where they reach a maximum diameter of 1cm. Packages are characterized by broad and tabular, sheet-like parted units which range upward from 2.1m to 10cm thick.

Abundant siltite interbeds characterize the uppermost unit (119-242 meters) of the Emerine Lookout section. This unit consists of about ninety fining-upward rock packages 30cm to 3.5m thick. Approximately one-third of the fining-upward packages contain lower and middle parts of medium to coarse-grained quartzite dominated by planar cross-bedding up to 45cm thick but also showing trough (up to 20cm thick) and low-angle (up to 10cm thick) cross-bedding and horizontal (up to 8cm thick) lamination. The upper parts of these packages consist of medium to fine-grained, horizontally laminated and/or ripple (up to 4cm thick) cross-bedded quartzite beds. Another third of the fining-upward packages contain similar lower and middle parts, but are characterized by horizontally (up to 1cm thick) laminated siltite or fine sandy siltite in their upper parts. Less common packages exhibit a complete upward-fining sequence from coarse to medium to fine sand to silt, and rare ones lack coarse sand. Irregular asymmetrical ripples with wavelengths of 10cm to 26cm and heights up to 3cm mark the upper surface of some medium to coarse-grained beds. Much of the coarser-grained quartzite contains subhorizontally oriented "mud chips" as large as 2cm by 10cm. Occasional basal surfaces of packages are scoured forming undulations less than 12cm deep, and many have load casts where underlain by siltite. Siltite intervals are thickest and most abundant in the lower third of unit 4.

They generally decrease upward in thickness and abundance to the top of the section. The top 4 meters of the section contain pebbles up to 7mm in diameter in two small gravel lenses. Most packages contain two parted units. The lower parted unit of each package consists of medium to coarse-grained quartzite and ranges from 2.7m to 15cm thick. The upper, finer-grained parted units are 90cm to 15cm thick.

Depositional environment. Fining-upward quartzite packages in unit 1 formed as braided channels of varying size aggraded their beds by deposition from lower, transitional, and upper flow regime bedforms. The dominance of tabular parted units in the lower and middle parts of each package reflects the dominance of flat-bottomed channels with high width/depth ratios during high and intermediate-stage flow. As discharge decreased, the broad channels split into small, shallow channels forming the lenses of medium to fine-grained sand which occupy the upper parts of the packages. Erosion of relatively fine sand and mud, evidenced by occasional mud clasts and scoured surfaces, occurred during rapid flow of some succeeding floods.

Unit 2 (62-84 meters) represents more competent braided channels of probably higher discharge whose floors were covered by lower to upper flow regime bedforms similar to those in the channels of unit 1. In addition to these bedforms, lag gravels and possibly small (15cm high by 12m long), longitudinal gravel bars formed in some parts of the channel floors under transitional and upper regime flow during high discharge.

Erosion scoured away the upper parts of some packages during rising or high-stage flow.

The absence of pebbles in unit 3 and the occasional siltite beds at the tops of fining-upward packages indicate decreased stream competence, velocity, and probably discharge. This change probably represents sourceward migration of the proximal, higher discharge alluvial plain facies (unit 2). Most packages in unit 3 very closely resemble those of unit 1 and reflect deposition by the same processes. Mud clasts in the coarser quartzites of many packages suggest scour of silt beds which capped the underlying packages. Where preserved, thinly-laminated siltite probably represents deposition of suspended sediment in abandoned channels or remnant channel ponds with little or no through-flowing current, or from overbank flooding adjacent to braided channels. Flat-bottomed channels with high (perhaps 100 or greater) width/depth ratios are suggested by the broad, sheet-like character of the parted units.

The distinct increase in number of siltite interbeds in unit 4 probably reflects an even lower-energy depositional environment. Such a change may reflect a general decrease in discharge and sediment influx into the system or possibly lateral migration of the more active part of the fan. Fining-upward packages which lack siltite represent channel-fill deposits similar to those previously described. The abundance of planar cross-beds in coarser-grained parts may be due to increased deposition by migrating transverse bars. Smith (1970) noted a marked downstream increase in the ratio of transverse to longitudinal bars and consequent distal increase in proportion of planar cross-beds in the Platte River. Packages capped by siltite or fine sandy siltite (Fig. 8) suggest a combination of bed load channel-fill and suspended load overbank deposition. The tabular shape and thin internal lamination which characterize parted units of siltite imply deposition of suspended load in ponds formed in broad, flat-bottomed, abandoned channels or from overbank flooding adjacent to active channels. Loadcasted surfaces indicate differential compaction of soft muds following burial by coarse sands. The absence of mudcracks in siltite beds suggests that the muds never fully dried out between floods. The progressive upward decrease in thickness and abundance of siltite interbeds throughout unit 4 and the presence of two small granule-pebble lenses at the top of the section may indicate a gradual upward trend of increasing stream competence and velocity.

Flint Creek Hill Section -- Lower Outcrop - Mount Shields Formation

Description. The top of the lower outcrop lies 170 meters (560 feet) down section from the base of the middle (Bonner) outcrop. Prominent features of the 48 meter (160 foot) lower outcrop are described below. See Appendix II for detail.

The predominantly purplish gray to light grayish white (minor light pink to pinkish gray) lower outcrop is composed almost entirely of fine or medium to fine-grained, horizontally (up to 2cm thick) laminated quartzite in even, tabular parted units 4cm to 40cm thick and at least 15m wide. The upper parts of parted units occasionally show ripple cross-bedding up to 3cm thick. Sinuous crested (?linguoid) ripples or straight-crested current ripples mark the upper bedding surfaces of some parted units. These ripples do not exceed 2cm in height or 8cm in wavelength. Occasional interbeds of medium or medium to coarse-grained quartzite form tabular parted units 30cm to 50cm thick which display trough cross-bedding up to 7cm thick, smaller low-angle cross-bedding, and ripple cross-bedding up to 3cm thick, as well as horizontal lamination up to 2cm thick. In the lower half of the outcrop, scattered thin (maximum 4cm), sheet-like parted units of brownish maroon, horizontally (maximum 5mm thick) laminated siltite overlie fine-grained quartzite. The tops of these units are commonly coated with a 1mm to 2mm thick clay layer usually showing polygonal mudcracks. Some clay-coated surfaces exhibit straight-crested, symmetrical ripples with 4cm to 6cm wavelengths. Angular to subangular "mud chips" up to 5cm long occur in occasional quartzite beds in the lower half of the outcrop, but are absent in the upper half.

Depositional environment. The predominance of medium to fine and fine-grained quartzite in the lower outcrop indicates deposition in a less competent fluvial environment than that in which the previously discussed sediments accumulated. As suggested by Winston (1978), the broad and flat tabular parted units and internal horizontal lamination probably represent upper flow regime deposition in very broad, flat-bottomed channels or on broad, low gradient sand flats, possibly during shallow sheetflood. Occasional ripple cross-bedding and current ripples on bedding surfaces reflect deposition from lower regime flow during waning discharge. Horizontally laminated fine sands which underlie silt beds probably also accumulated during lower regime flow. Thicker parted units of medium or medium to coarse-grained quartzite most likely reflect the minor occurrence of deeper, more competent stream channels flowing across the area. Thin internal lamination of the siltite beds in the lower half of the outcrop suggests lower flow reigme plane bed or suspended load deposition as flow velocity slackened and came to a halt. The upper silt and thin clay laminae probably settled from still water in large but shallow ponds on the fan surface. Symmetrical ripples formed on the bottoms of some ponds as wind-generated waves crossed their surfaces. Eventually, ponds dried up and their muddy bottoms cracked apart. Reworking of some muds by later flood events supplied mud clasts to overlying sandy strata.

Flint Creek Hill -- Middle Outcrop - Bonner Formation

Description. Salient characteristics of the 91 meter (300 foot) middle outcrop are described in three units. See Appendix II for detail.

The lowermost unit (0-42 meters) is composed of three 7m to 8m thick intervals of uniform, relatively coarse quartzite interbedded with sequences of thinner, fining-upward quartzite packages. The fining-upward packages are most abundant in the lower third of unit 1, and they range from 45cm to 2.2m thick. Packages are composed of medium to coarse-grained, trough (maximum 20cm thick), planar (maximum 30cm thick), and/or low-angle cross-bedded and horizontally (maximum 8cm thick) laminated quartzite in their lower and middle parts overlain by relatively thin intervals of medium to fine-grained, horizontally (up to 3cm thick) laminated and (minor) planar (up to 10cm thick) and small ripple (up to 1cm thick) cross-bedded quartzite. The thick intervals of uniform quartzite occur in the upper two-thirds of unit 1. They contain mostly coarse-grained quartzite with internal structure similar to that in the lower and middle parts of the fining-upward packages, but this quartzite becomes coarse to very coarse-grained with minor scattered pebbles up to 1cm in diameter in the upper part of unit 1. A few parted units within the uniform intervals contain scattered mud clasts up to 1cm by 4cm, and some have scoured basal surfaces.

Unit 2 (42-70 meters) is dominated by four thick (4.5-8 meter) intervals of medium to very coarse-grained, trough, planar, and low-angle cross-bedded and horizontally laminated quartzite containing interbedded conglomerate lenses or scattered pebbles. Scattered pebbles lie along the foresets of some planar cross-beds. Matrix-supported gravel occurs in horizontal lenses generally not greater than 20cm thick, or in flat and thin (4cm thick and greater than 8m wide) concentrations at the tops of parted units. Most pebbles do not exceed 3.5cm in diameter, but the largest measures 6.5cm. Most of the conglomerate lacks internal structure, but some exhibits low-angle cross-bedding. Each of the thick, coarse intervals is capped by a rather thin (20-60cm) interval of horizontally (up to 4cm thick) laminated, medium to fine-grained quartzite.

Approximately thirty percent of the upper unit (70-91 meters) lies beneath a cover of loose rock and dirt. The exposed part, however, consists of seven fining-upward quartzite packages 60cm to 2.8m thick. The packages contain medium to coarse-grained, trough, planar, and/or low-angle cross-bedded and/or horizontally laminated quartzite in their lower and middle parts overlain by medium to fine-grained, horizontally laminated and (minor) ripple cross-bedded quartzite in their upper parts. Except for a 15cm thick by 1.5m wide conglomerate lens within the lower third of unit 3, the unit contains no pebbles.

Depositional environment. Fining-upward packages comprising the lower third of unit 1 suggest channel-filling in braided channels very similar to those which deposited unit 1 of the Copper Creek and Emerine Lookout sections. The thick, coarse-grained quartzite intervals which dominate the upper two-thirds of the unit probably represent the progressive development of larger, more competent braided channels. The coarse quartzites formed in the same way as those in the lower and middle parts of the fining-upward packages. The absence of finer material and the occasional presence of mud clasts and scour surfaces probably reflect increased erosion during high-stage flow.

As in the other three sections, unit 2 (42-70 meters) is the coarsest-grained portion of the section and represents deposition in a higher-energy environment than that in which the rest of the section accumulated. The medium-grained to conglomeratic quartzite which dominates the unit was most likely deposited during high discharge in braided channels in upper and lower regime flow. Thin sheets of lag gravel and small longitudinal gravel bars up to about 20cm high covered parts of the sandy channel bottoms. Some other parts contained only scattered pebbles. The small amounts of medium to fine-grained quartzite reflect deposition in flat and smooth-bottomed, smaller channels during low discharge.

The general lack of pebbles or conglomerate and the relatively thin character of fining-upward packages in unit 3 indicates the return of less competent, probably smaller braided streams. The packages formed by vertical aggradation in broad and shallow channels. Deposition from lower to upper flow regime bedforms as flow depth and velocity gradually declined produced packages with highly variable sedimentary structures and a general upward decrease in scale of these structures.

Flint Creek Hill Section -- Upper Outcrop - McNamara Formation

Description. The base of the upper outcrop occurs 275 meters (910 feet) up section from the top of the middle (Bonner) outcrop. Grain size and rock color remain essentially constant throughout the 42 meter (140 foot) upper outcrop, but only the lower 18 meters (60 feet) provide sufficient exposure for detailed description. Conspicuous characteristics are mentioned below and Appendix II gives more detail.

The predominantly light gray to light grayish white (minor purple to purplish gray) upper outcrop consists of medium to fine-grained quartzite in tabular or lenticular parted units commonly 20cm to 1m thick. Some parted units show horizontal lamination up to 6cm thick, while others exhibit large-scale trough cross-bedding in cosets ranging from 10cm thick by 1.2m wide to 60cm thick by greater than 2.5m wide. Trough-shaped cosets show internal, concave-up, parallel lamination up to 1cm thick, and the lower surfaces of some cosets truncate internal lamination of underlying cosets. Horizontal lamination and trough cross-bedding occur in approximately equal amounts, and they generally alternate vertically every 50cm to a meter or so. Brownish maroon, angular to subrounded mud clasts are very abundant throughout the outcrop and exist in parts of almost every parted unit. Mud clasts reach 5cm in length, but most range from 2mm to 3cm. They normally lie flat along bedding planes and their numbers vary from minor scattered flakes to very closely-packed concentrations covering almost 50% of the bedding surface.

Depositional environment. The relatively fine grain size of the upper outcrop indicates deposition in a less competent environment than that in which sediments of the middle outcrop accumulated. Horizontally laminated sands probably represent upper flow regime deposits in wide, flat-bottomed channels, whereas the trough cross-bedded sands reflect downstream migration of large-scale, lower regime bedforms such as sinuous-crested or lunate dunes or sinuous-crested transverse bars (e.g. Williams, 1971). Erosional bases of trough-shaped cosets and the unusual abundance of matrix-supported mud clasts imply that silt was commonly deposited and then later scoured away and reworked into overlying sandy beds.

CHAPTER IV

PALEOCURRENT ANALYSIS

Dip directions of forty-four separate sets of planar cross-beds were measured at Emerine Lookout to determine flow direction of the depositional currents. For each set of cross-beds, the orientations of two apparent dips were measured, and with the use of an equal-area net this data allowed calculation of the true dip orientation. True dips are assumed to represent local current flow direction since planar cross-beds form as sands avalanche down a slip face oriented more or less perpendicular to the current. True dip bearings, illustrated in Figure 9, reveal a dominant north-northeast current flow direction. In addition, thirty-two apparent dip directions, half from Emerine Lookout and half from Wise River, support the same north-northeast current trend. Apparent dips, however, should be considered only as very general current direction indicators.

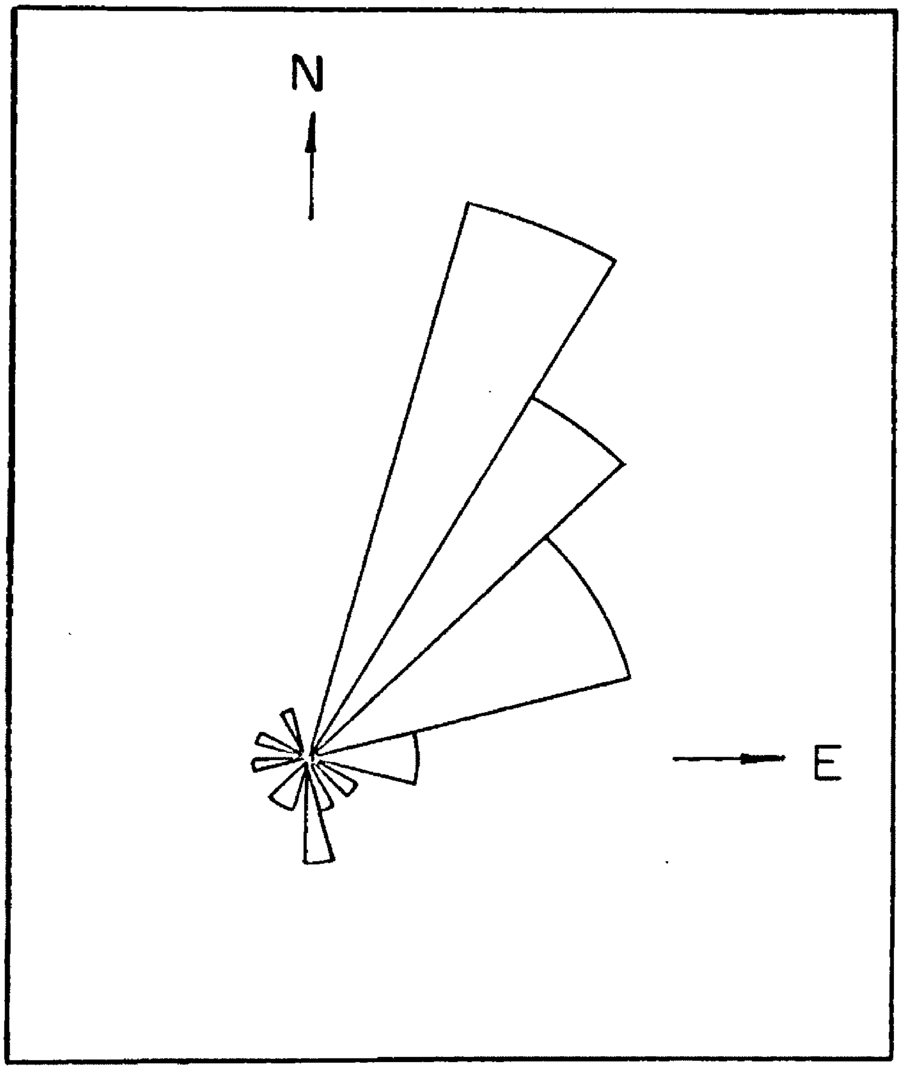


Figure 9. Rose diagram illustrating directional paleocurrent data (planar cross-bed true dips) from 44 measurements at Emerine Lookout. Note dominant N-NE flow direction.

CHAPTER V

REGIONAL CORRELATION AND STRATIGRAPHY

Regional Correlation

The conglomeratic interval forms a very distinct unit which is clearly recognizable in the sections at Wise River, Copper Creek, Emerine Lookout, and Flint Creek Hill (see Appendix II). Correlation of the four sections is based primarily on the presence of this uniquely coarse-grained unit. Figures 10 and 11 illustrate the continuity of the conglomeratic interval on both a local and a regional scale. No other parts of the Missoula Group are known to contan gravels nearly so coarse as these. Furthermore, the progressive, systematic northward decrease in size of cobbles, pebbles, and gravel lenses (Fig. 12) supports the interpretation that the conglomerate represents a single unit deposited contemporaneously by a northward distributing stream system. Thin conglomerate lenses occur locally at the top and bottom of medium to fine-grained quartzite of the Mount Shields sandstone member. Conglomerate of the Mount Shields differs from that of the Bonner, however, by containing pebbles no larger than 2cm in diameter. Even more importantly, pebbles and cobbles in the Bonner gravels are almost entirely purple, red, gray, or white quartz and quartzite, whereas the Mount Shields conglomerates commonly contain between thirty and fifty percent pink granitic pebbles. Some matrix sand of the Mount Shields conglomerates is medium

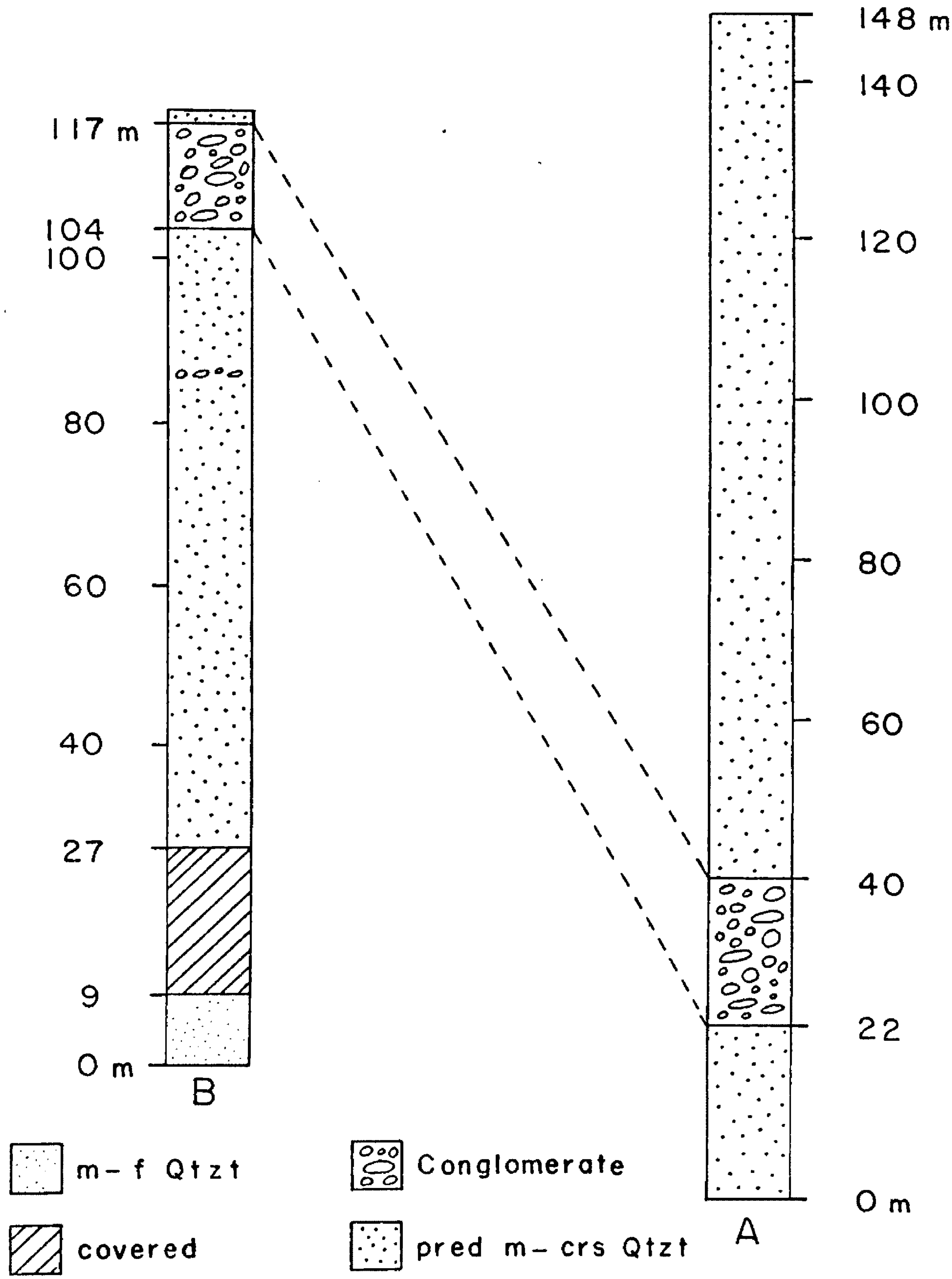


Figure 10. Generalized stratigraphic sections from Wise River showing lateral continuity of conglomeratic interval. A = main section described in Appendix II and Chapter 3. B = section measured approximately [illegible] west (horizontally) of section A.

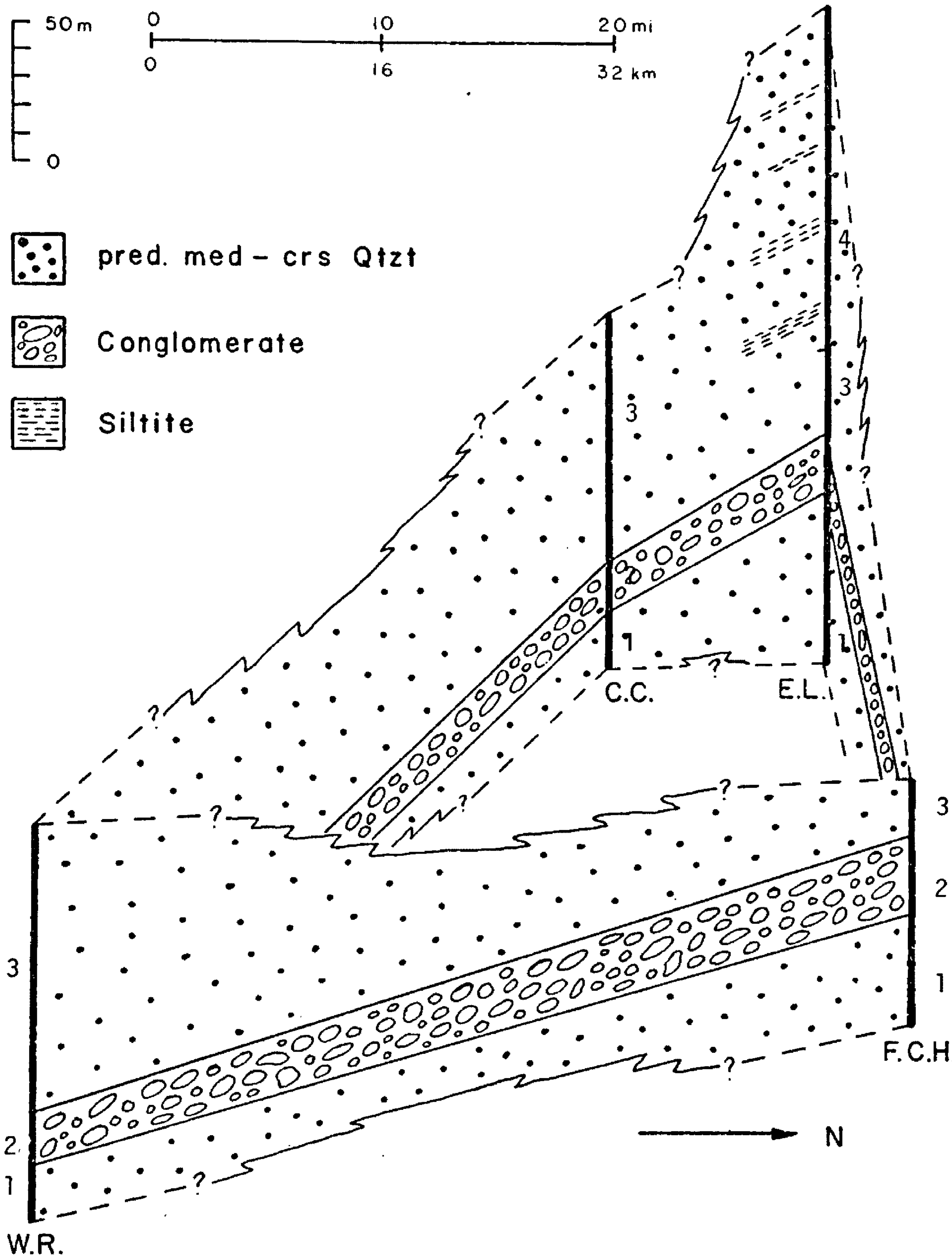


Figure 11. Fence diagram showing regional continuity of conglomeratic interval (unit 2). Numbers indicate units described in each section.

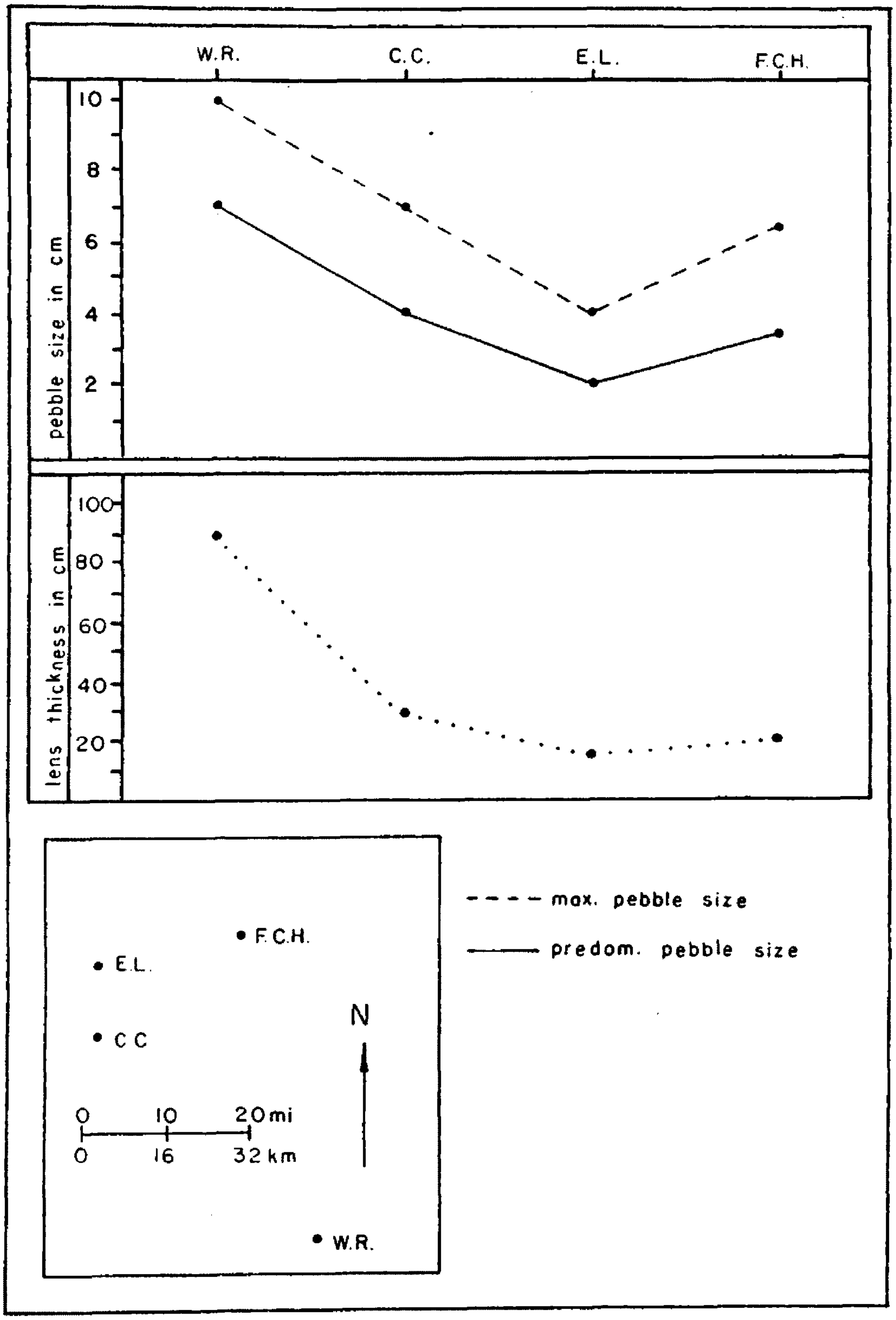


Figure 12. Plot of size data for gravel clasts and lenses showing general northward decrease in size of both. Inset shows section locations with respect to northerly direction.

to fine-grained, but all the sand matrix of the Bonner gravels is medium to very coarse-grained.

Unit 1 of each section is correlated on the basis of similar lithology, sedimentary structures, and position below the conglomeratic interval (see Fig. 11). At Wise River this unit is uniformly medium to coarse-grained quartzite, but in the other sections unit 1 is composed of fining-upward quartzite packages whose upper parts are medium to fine-grained.

As previously mentioned, unit 2 is uniquely coarser-grained than any other parts of the sections. At Wise River unit 2 contains gravel lenses up to 90cm thick with subhorizontally oriented cobbles up to 10cm in diameter. Conglomerate in lenses up to 30cm thick and in rare thin sheets is interbedded with medium to very coarse-grained, horizontally laminated or low-angle cross-bedded quartzite in unit 2 at Copper Creek. At Emerine Lookout and Flint Creek Hill, thin gravel layers and lenses as thick as 20cm occur in horizontally laminated to high-angle cross-bedded quartzite packages which are medium to fine-grained in their upper parts.

Unit 3 of each section is correlated on the basis of position above unit 2 and similarity of fining-upward rock packages which comprise the units. The majority of packages range from 50cm to 2m thick, and are composed of medium to coarse-grained quartzite in their lower and middle parts overlain by medium to fine-grained quartzite in their upper parts. A general upward decrease in scale of cross-bedding and horizontal lamination accompanies the decrease in grain size.

Unit 4 of the Emerine Lookout section resembles unit 3 of all four sections in that it lacks pebbles and is composed of fining-upward packages. It was differentiated, however, because approximately one-third of the packages contain horizontally laminated siltite in their upper parts. Based on stratigraphic height above the conglomeratic interval, the lower part of unit 4 is correlated with the upper part of unit 3 at Wise River and Copper Creek (see Fig. 11).

History of Stratigraphic Nomenclature

Belt stratigraphy has provided a continuous challenge to geologists since the rocks were first studied in northwestern Montana (Willis, 1902; Walcott, 1906) in the early 1900's. Calkins and Emmons (1915) originally described the Philipsburg Quadrangle and referred to the reddish sandstones and shales above the middle-Belt carbonate as the Spokane Formation. Sixteen years later, similar rocks were described near Missoula by Clapp and Deiss (1931), and given the name Missoula Group. As originally subdivided, this group contained the following formations (oldest to youngest): Miller Peak, Hellgate, McNamara, Garnet Range, and Sheep Mountain. Clapp and Deiss correlated the Spokane Formation of Calkins and Emmons (1915) with their Miller Peak and Hellgate formations. Later, detailed work near Missoula by Nelson and Dobell (1961) resulted in modification of Missoula Group nomenclature (Fig. 13). They reduced the Hellgate to a discontinuous quartzite member of the Miller Peak Formation, coined the name Bonner Quartzite for what was

Formations	CLAPP and DEISS - 1931	NELSON and DOBELL - 1961	HARRISON - 1972
	Sheep Mountain	Pilcher	Pilcher
	Garnet Range	Garnet Range	Garnet Range
	McNamara	McNamara	McNamara
		Bonner	Bonner
	Hellgate	(Hellgate Quartzite Member)	Mount Shields
		Miller Peak	Shepard
	Miller Peak		Snowslip

Figure 13. Evolution of Missoula Group nomenclature.

previously the middle part of the McNamara, and renamed Sheep Mountain rocks the Pilcher Quartzite. These changes gave rise to the following sequence of formations: Miller Peak, Bonner, McNamara, Garnet Range, and Pilcher. Childers (1963) mapped in the lower part of the Missoula Group three formations near Marias Pass. He named the Snowslip and Mount Shields formations and redefined the Shepard Formation named by Willis (1902). Harrison (1972) and Wallace (1978) have extended these units into the study area, so that the Miller Peak Formation is supplanted by the Snowslip, Shepard, and Mount Shields formations. Thus, modern terminology for the formations of the Missoula Group is as follows: Snowslip, Shepard, Mount Shields, Bonner, McNamara, Garnet Range, and Pilcher.

Definition of the Bonner Formation

Nelson and Dobell (1961) originally described the Bonner Formation at the type locality two miles east of Bonner as a quartzite with a dominant grain size of 0.5mm. The quartzites described in this study are closer to the source area and are generally as coarse or coarser than is the Bonner at the type locality. The finer-grained quartzite below the Bonner belongs to the Mount Shields Formation, the finer-grained quartzite above the Bonner belongs to the McNamara Formation. The section at Flint Creek Hill was measured from within the Mount Shields upward through the Bonner and into the lower McNamara Formation. The contacts are not exposed at Flint Creek Hill. However, the lowermost part of the Bonner is predominantly medium to coarse-grained, relatively large-scale cross-bedded quartzite, whereas the uppermost part of the Mount Shields Formation is medium to fine or fine-grained, horizontally laminated and (minor) ripple cross-bedded quartzite. The uppermost part of the Bonner is very similar to the lowermost part, whereas the lowermost part of the McNamara Formation is medium to fine-grained, horizontally laminated or very large-scale trough cross-bedded quartzite containing abundant mud clasts along bedding planes. The Bonner Formation is thus defined here as the predominantly medium to coarse to pebbly quartzite unit.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Integrated Interpretation

Sediments of the Missoula Group have been interpreted by Winston (1973b, 1977, 1978), Bleiwas (1977), and Lemoine (1979) as alluvial fan, fan delta, and shallow "marine" deposits. The absence of vegetation in the Precambrian greatly favored the formation of braided streams as land masses were weathered and eroded by rain-drop splash and sheetwash runoff. Winston (1973b, 1977, 1978) has developed a fluvial facies model (Fig. 3) for the Missoula Group based primarily on investigation of the Bonner and Mount Shields Formations. He distinguishes five rock types, each reflecting a particular level or region on alluvial fan, distal flat, and sea margin surfaces. In Winston's model, conglomeratic quartzite high on the fan nearest the source passed downslope to coarse, cross-bedded quartzite which eventually graded into fine, horizontally laminated quartzite on the lower, flatter reaches of the fan. The Bonner of this study corresponds to the conglomeratic rock type and the coarse, cross-bedded rock type of Winston. At Flint Creek Hill, the lower outcrop (Mount Shields Formation) represents the fine, horizontally laminated rock type, and a modified version of this rock type constitutes the upper outcrop (McNamara Formation). Based on the data of this study, and on previous work by Winston and Bleiwas, I interpret the Bonner Formation as channel-fill deposits of braided channels crossing the upper and middle reaches of large alluvial fans. These braided streams were probably most similar to the "Platte type" of Miall (1977). Paleocurrent data, as well as the northward decrease in size of gravel lenses and clasts indicate a general north-northeast flow direction and a sediment source to the south or southwest. While previous studies have proposed a source area south of the Willow Creek fault in crystalline plutonic and metamorphic rocks of the uplifted Dillon Block (Harrison, Griggs and Wells, 1974) it seems likely that Precambrian highlands to the west of the Dillon Block, such as the Lemhi Arch (Ruppel, 1978), were perhaps the chief sediment contributors.

As the lower parts (unit 1) of the sections accumulated on the extensive, northward sloping fan surface, the medium to coarse sands at Wise River aggraded the broad and flat bottoms of highly competent, braided stream channels. Due to rapid flow conditions, finer-grained material was either not deposited or was scoured away during rising flood discharge. To the north, the streams flowed slower across the gentler slopes resulting in deposition and preservation of fine as well as coarse-grained sands. The scattered mud clasts indicate that stream power was still strong enough to scour silt deposits. Periodic flood discharges sweeping across this region of the fan formed fining-upward quartzite packages as the discharge decreased. These packages exist today at Copper Creek, Emerine Lookout, and Flint Creek Hill. The decrease in stream competence could have resulted from at least two different processes. The first, and most obvious, is simply the gradual waning and dying out of individual flood events. The second has been discussed by Miall (1977), p. 43), and may have occurred a number of times during a single flood. Sedimentation in a particular channel would result in aggradation above the surrounding area and a progressive reduction of slope. The decreased gradient would decrease stream velocity and competence, and channel-floor aggradation would result in a gradual shallowing of the stream and upward fining of the sediment. As the channel became filled with sediment, channel systems would be diverted into topographically lower areas. These new areas would then undergo sedimentation and the process would be repeated producing tabular, upward aggrading packages with sharp bases. Thus, the tabular, fining-upward packages could be the records of single floods or of major channel shifts during single flow events. Since both processes would form nearly identical sequences, it is impossible at this time to interpret which process produced the fining-upward, tabular packages. However, both processes may have been involved.

The conglomeratic interval (unit 2) in each of the four sections represents an extensive "gravel sheet" which temporarily advanced down-slope as the entire depositional system prograded or expanded northward. Progradation may have resulted from a marked increase in precipitation and discharge rates or from uplift of the source area. During this period, large streams nearest to the source area (Wise River section) flowed predominantly in the upper regime. Longitudinal gravel bars up to 90cm high with cobbles up to 10cm in diameter occupied parts of the flat, sandy channel bottoms. Upper regime conditions continued to dominate channel flow farther downslope, but stream competence and probably size decreased. In this region of the fan (Copper Creek section), longitudinal gravel bars reached only 30cm high and pebble size did not exceed 7cm. In addition to the gravel bars, rare thin sheets of lag gravel stretched across parts of some channel floors. During maximum discharge, these channels may have been on the order of 3m deep and 450m wide. With the progressive drop in gradient down the fan surface, braided streams in areas farther north (Emerine Lookout and Flint Creek Hill sections) deposited sediment under lower as well as upper regime flow. Pebbles up to 4cm in size accumulated in relatively small (up to 20cm high) longitudinal bars or in thin lag-gravel accumulations. The higher coarse sand to conglomerate ratio of these deposits reflects the increased distance from the source. In this lower-discharge environment, medium to fine sands deposited during low discharge, as well as coarser material, were preserved.

The absence of conglomerate and the predominance of fining-upward rock packages in unit 3 of each section indicate the return of less competent streams almost identical to those in which unit 1 accumulated. Therefore, the factors reponsible for progradation of the fan must have gradually exhausted their influence. The fining-upward packages represent channel-filling through vertical aggradation in braided channels probably on a scale of 50cm to 2m deep and 75m to 300m wide. As flow depth and velocity of individual flood events gradually declined, the scale of bedforms on channel bottoms and the grain size of sediment being deposited decreased.

The abundant siltite interbeds in the upper part (unit 4) of the Emerine Lookout section reflect a further drop in energy of the depositional system. This change is not apparent at Wise River or Copper Creek, where stratigraphically continuous levels of the section are exposed. The thinly laminated siltite beds probably formed by deposition of suspended load from ponds in broad, flat-bottomed, abandoned channels or from overbank flooding adjacent to active channels. This type of deposition suggests relatively low-gradient streams possibly resulting from lateral migration of a main distributary lobe of the fan, coupled with continual subsidence of the fan surface.

The medium to fine grain size of the Mount Shields and McNamara Formations at Flint Creek Hill indicates that they were deposited in a less competent depositional setting than was the Bonner. The relatively fine-grained sands probably accumulated in wide distributary channels or on broad sand flats on the lower reaches of the alluvial fan. Thus, the entire Bonner Formation represents a distinct episode of northward progradation of the alluvial fan - fan delta system infilling the southern portion of the "Belt Sea". Possible causes of such an event include climatic change to a much wetter environment resulting in increased runoff and discharge, or significant uplift of the source area giving rise to more rapid rates of erosion and increased sediment influx.

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APPENDIX I

LOCATION OF MEASURED SECTIONS

LOCATION OF MEASURED SECTIONS

Flint Creek Hill Section

The Flint Creek Hill section was measured at the shared corner of sections 25, 26, 35, and 36, T.6N., R.14W. on the U.S. Forest Service Deerlodge National Forest map. The section includes three nearly vertical roadcuts along the northeast side of U.S. highway 10-A in the vicinity of Flint Creek campground between Skalkaho Road (Forest Route 16) and Georgetown Lake. The lowest (stratigraphically) outcrop occurs approximately 50 meters uphill from mile marker #30. Downhill (up section) between mile marker #30 and the entrance to Flint Creek campground, lies the middle outcrop. The third outcrop occurs approximately 300 meters downhill from the campground entrance.

Emerine Lookout Section

The Emerine Lookout section was measured in the northwest 1/4 of section 8, T.5N., R.16W. on the U.S. Forest Service Deerlodge National Forest map. Access to the section is provided by a logging road which turns south off of Skalkaho Road approximately three miles west of its intersection with Rock Creek Road. A steep northeast facing cirque wall just north of the lookout affords good exposure. The section begins at the lowest outcrop on bearing S.57W. from the center of a small lake in the base of the cirque and continues up the steep slope and along a narrow notch in the upper half until it reaches the top just north of the lookout.

Copper Creek Section

The Copper Creek section is located in the northeast 1/4 section 26, T.4 N., R.16W. on the U.S. Forest Service Deerlodge National Forest map. The section was measured through discontinuous outcrop on the southeast slope of the northeast trending ridge north of Copper Creek. To reach the base of the section, one must start at the Copper Creek campground and traverse approximately N.30W. through a wooded area to the base of the ridge, and then up the talus slope to the lowest outcrop.

Wise River Section

The Wise River section was measured in the northwest 1/4 of the southeast 1/4 of section 36, T.1S., R.12W. on the U.S. Forest Service Beaverhead National Forest map (west half). A 90 to 120 meter (300 to 400 foot) high vertical cliff surrounded by coarse talus slopes crops out on the northwest side of Forest Route 484 (Wise River Road) opposite an elk ranch approximately seven miles southwest of the town of Wise River. A U.S.G.S. stream gauging station and a small wooden bridge also occur next to the road at this location. The section begins at the lowest exposure in the cliff and continues up the talus slope along the west side of the cliff base.

APPENDIX II

MEASURED SECTIONS

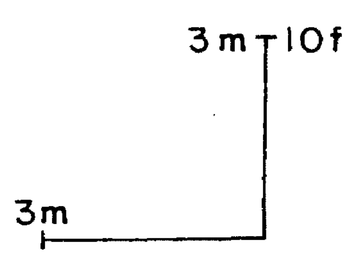
EXPLANATION

Grain Size (Wentworth Scale)

- Gravel
- Very coarse sand
- Coarse sand
- Medium sand
- Fine sand
- Silt

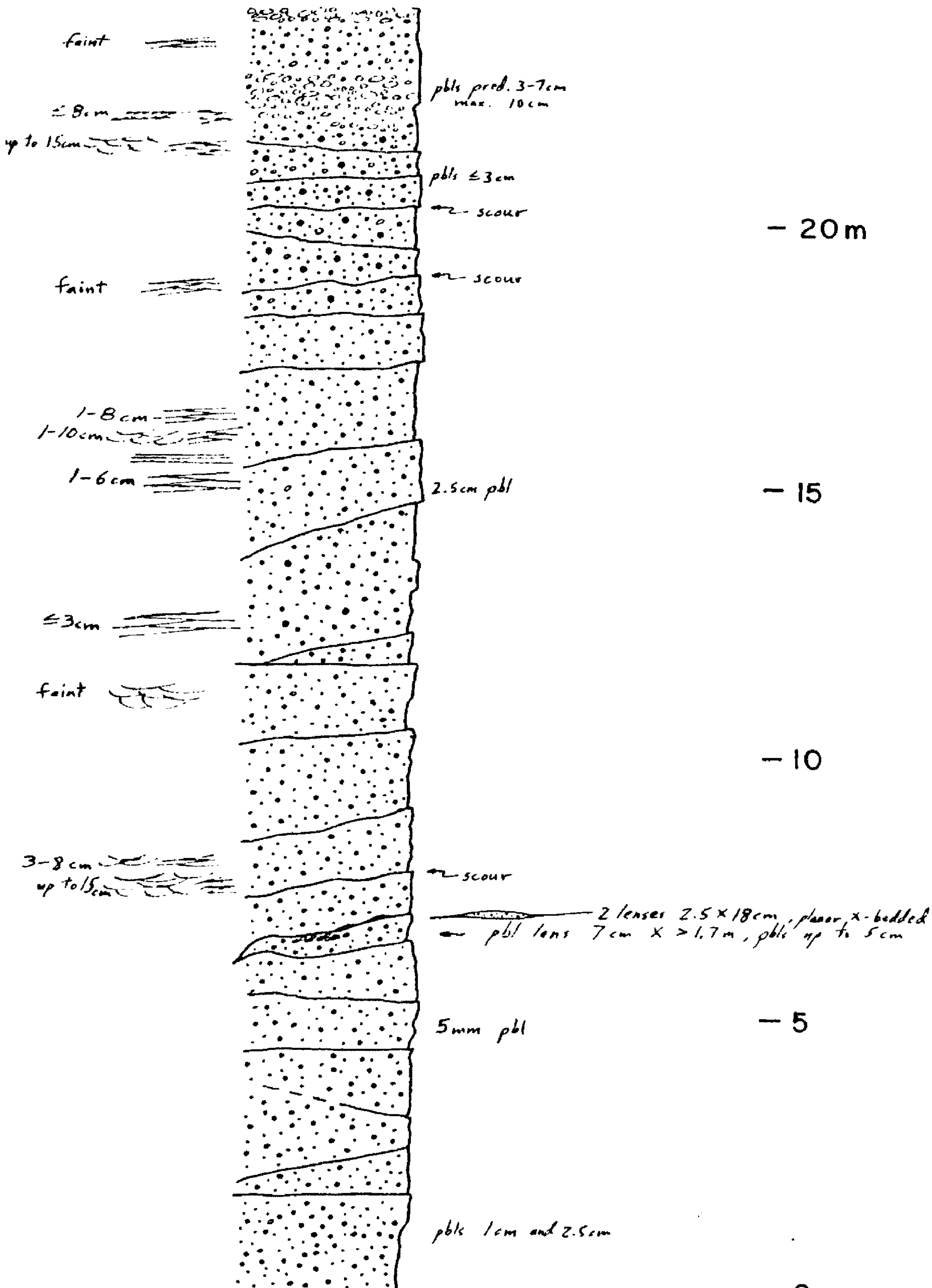
Sedimentary Structure

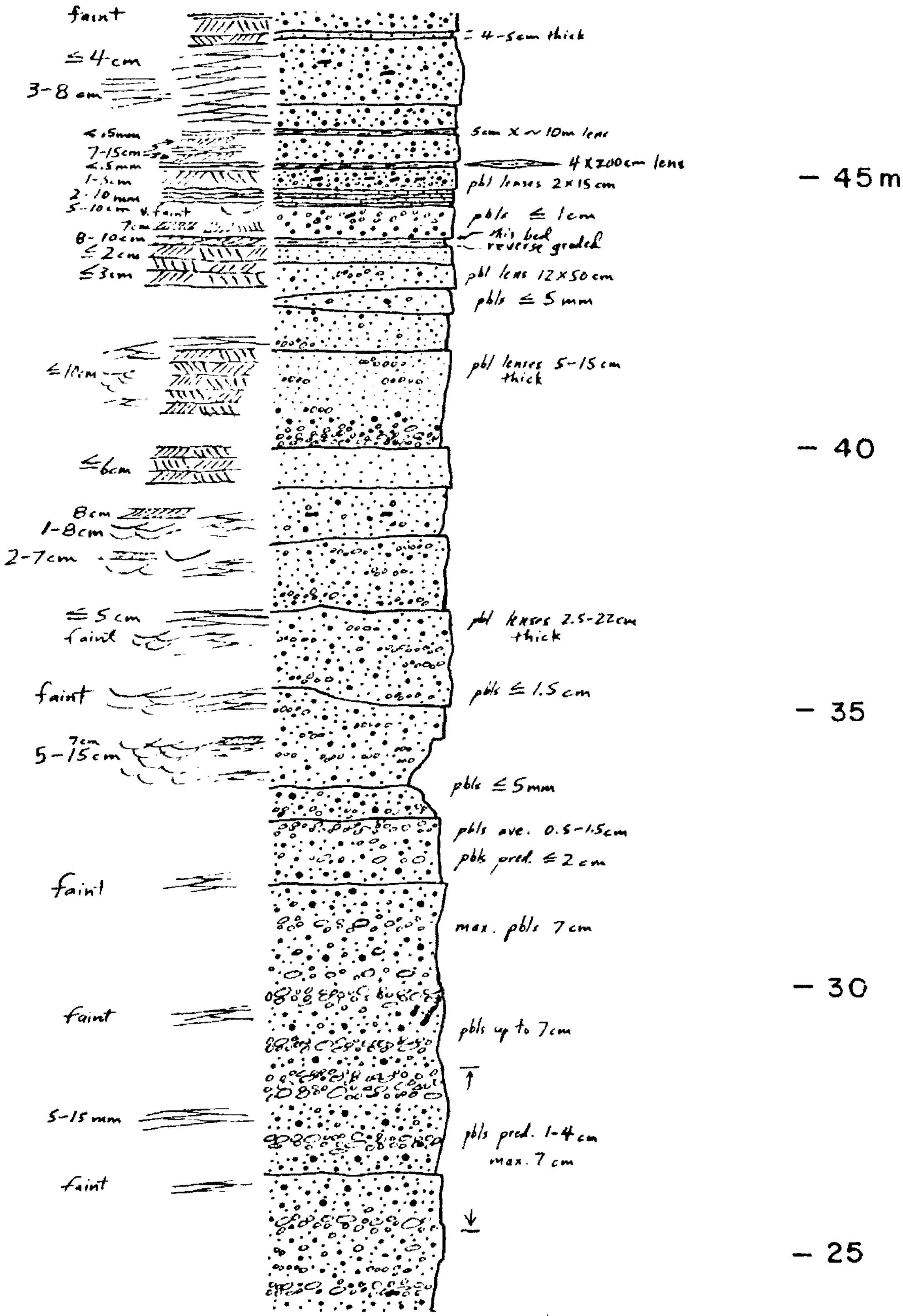
- Trough cross-bedding
- Planar cross-bedding
- Ripple cross-bedding
- Low-angle cross-bedding
- Horizontal lamination or bedding
- Mudcracks
- Mud clasts

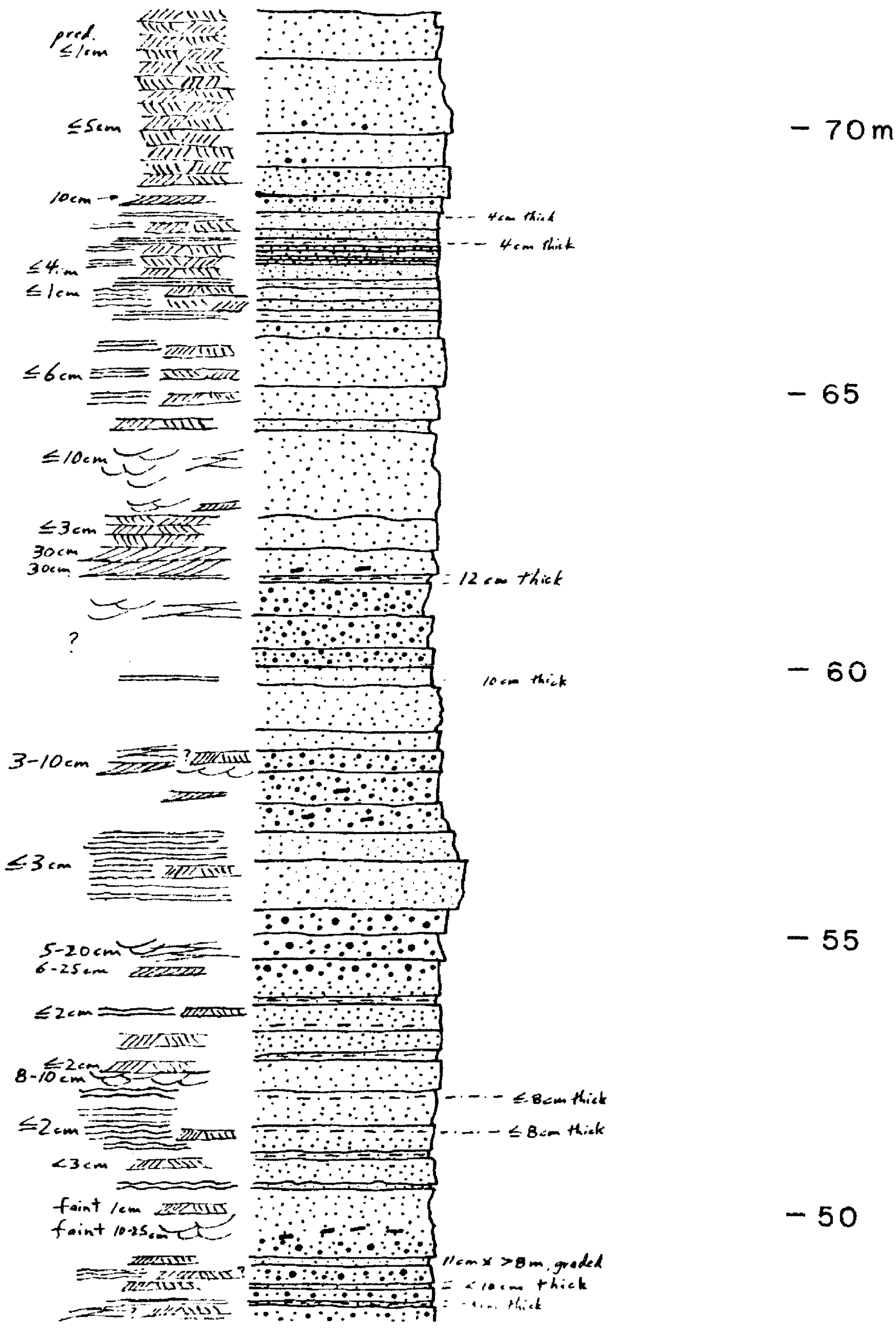


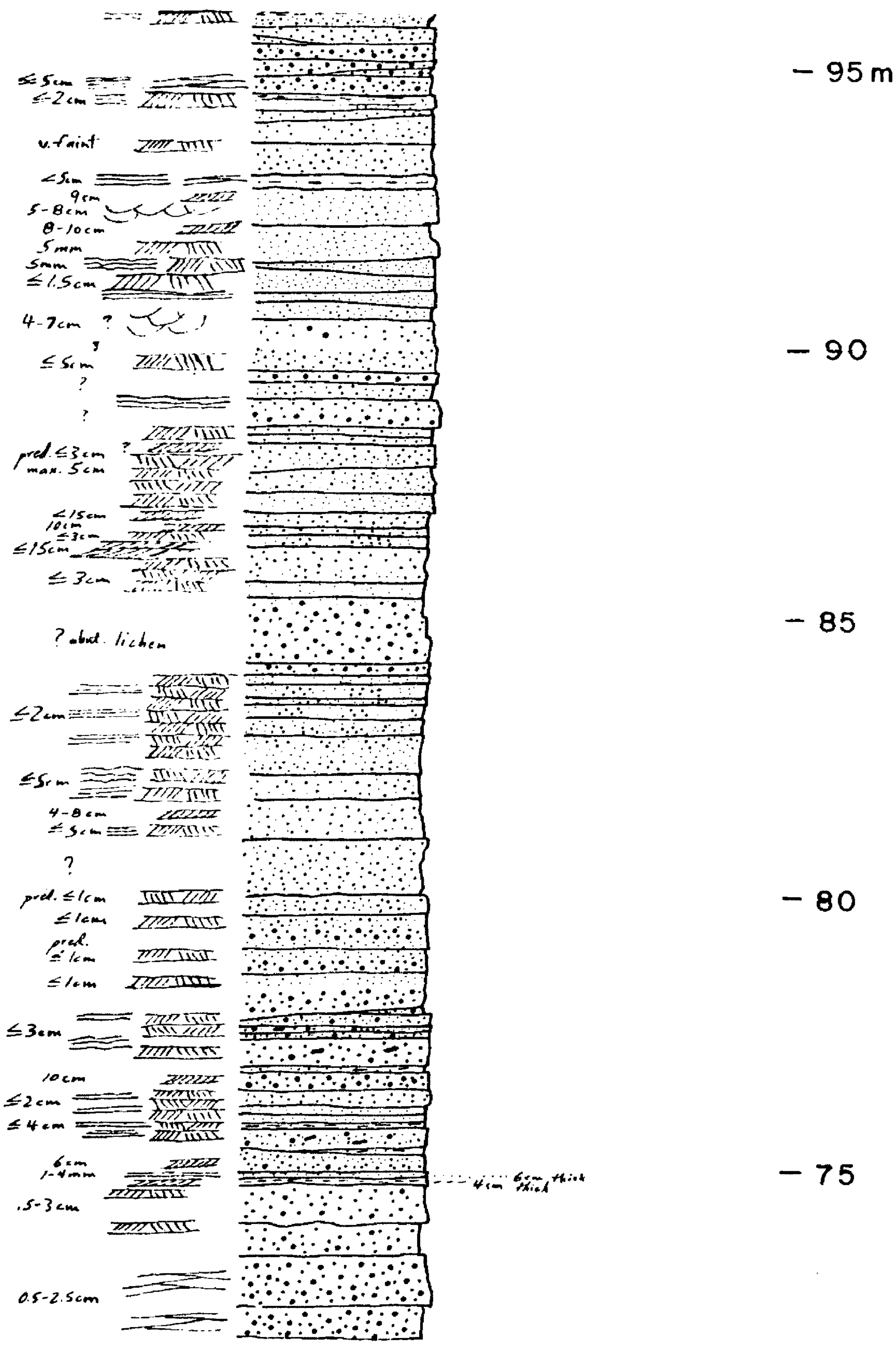
Scale

WISE RIVER

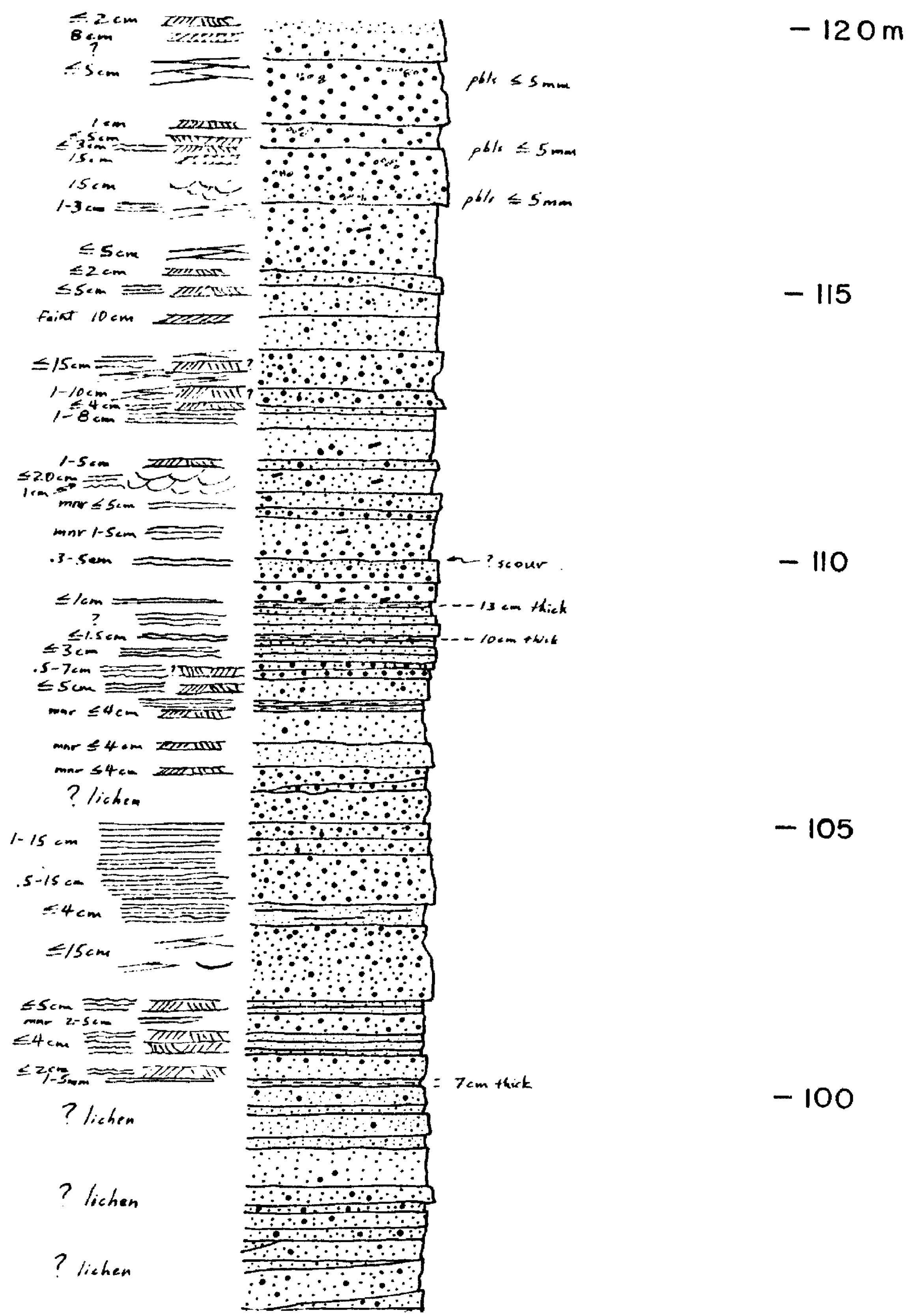

faint
pbls pred. 3-7cm
max. 10cm
≤ 8cm
up to 15cm
pbls ≤ 3cm
scour
20m
faint
scour
1-8cm
1-10cm
1-6cm
2.5cm pbl
15
≤3cm
faint
10
3-8cm
up to 15cm
scour
2 lenses 2.5 × 18cm, planar, x-bedded
pbl lens 7cm × >1.7m, pbls up to 5cm
5mm pbl
5
pbls 1cm and 2.5cm
0


faint
≤ 4-cm
3-8 cm
4-5cm thick
5cm x ~10m lens
4 x 200cm lens
pbl lenses 2 x 15 cm
pbls ≤ 1cm
this bed reverse graded
pbl lens 12 x 50 cm
pbls ≤ 5 mm
pbl lenses 5-15 cm thick
≤ 6cm
8cm
1-8cm
2-7cm
≤ 5 cm
faint
pbl lenses 2.5-22cm thick
faint
pbls ≤ 1.5 cm
7cm
5-15cm
pbls ≤ 5mm
pbls ave. 0.5-1.5cm
pbls pred. ≤ 2 cm
faint
max. pbls 7 cm
faint
pbls up to 7cm
5-15 mm
pbls pred. 1-4cm max. 7 cm
faint
— 45m
— 40
— 35
— 30
— 25

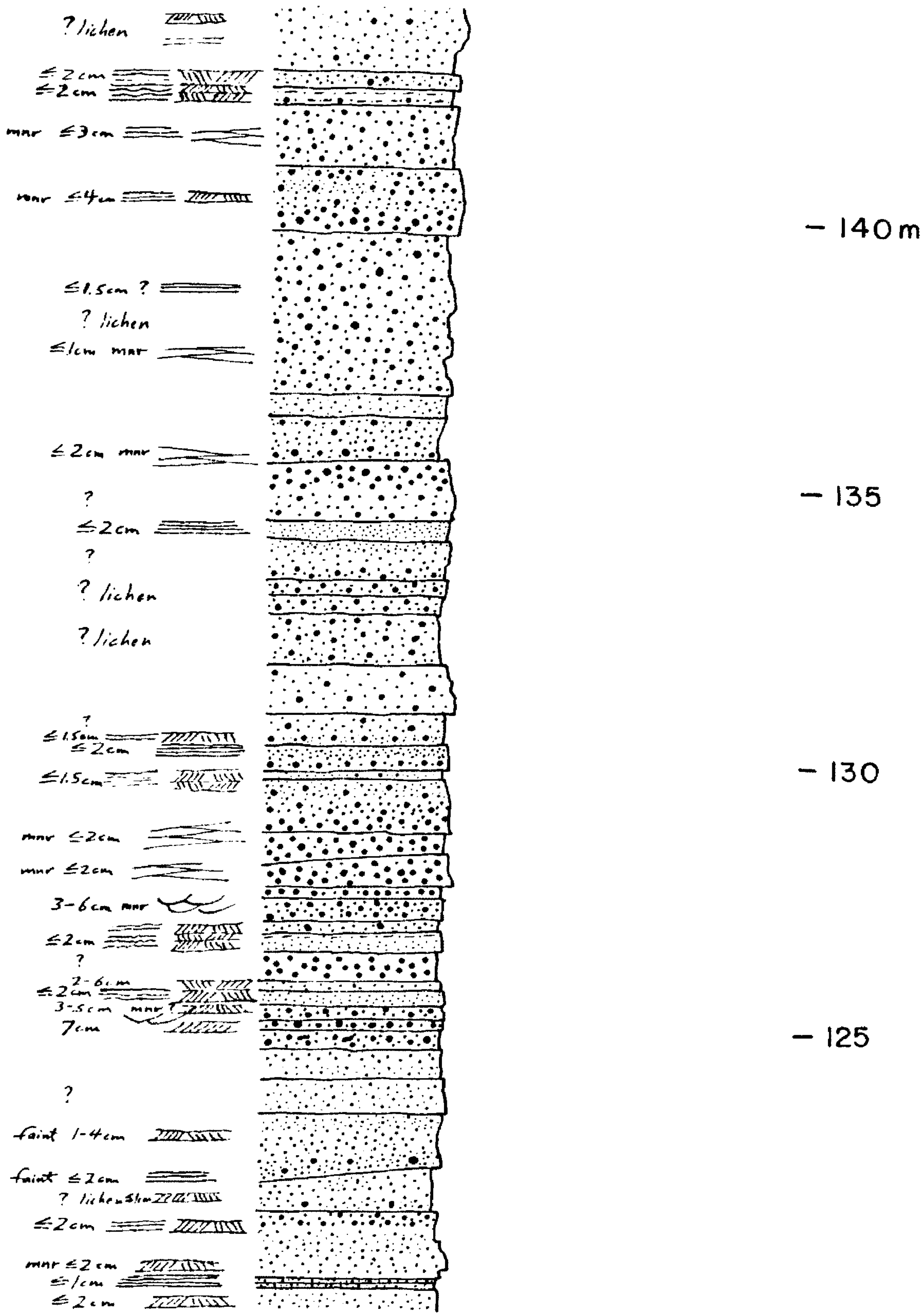

pred. ≤1cm
≤5cm
10cm
≤4cm
≤1cm
≤6cm
≤10cm
≤3cm
30cm
30cm
?
3-10cm
≤3cm
5-20cm
6-25cm
≤2cm
≤2cm
8-10cm
≤2cm
<3cm
faint 1cm
faint 10-25cm
4cm thick
4cm thick
12cm thick
10cm thick
≤8cm thick
≤8cm thick
11cm x >8m, graded
<10cm thick
– 70m
– 65
– 60
– 55
– 50



95 m
90
85
80
75
? abnt. lichen
0.5-2.5cm

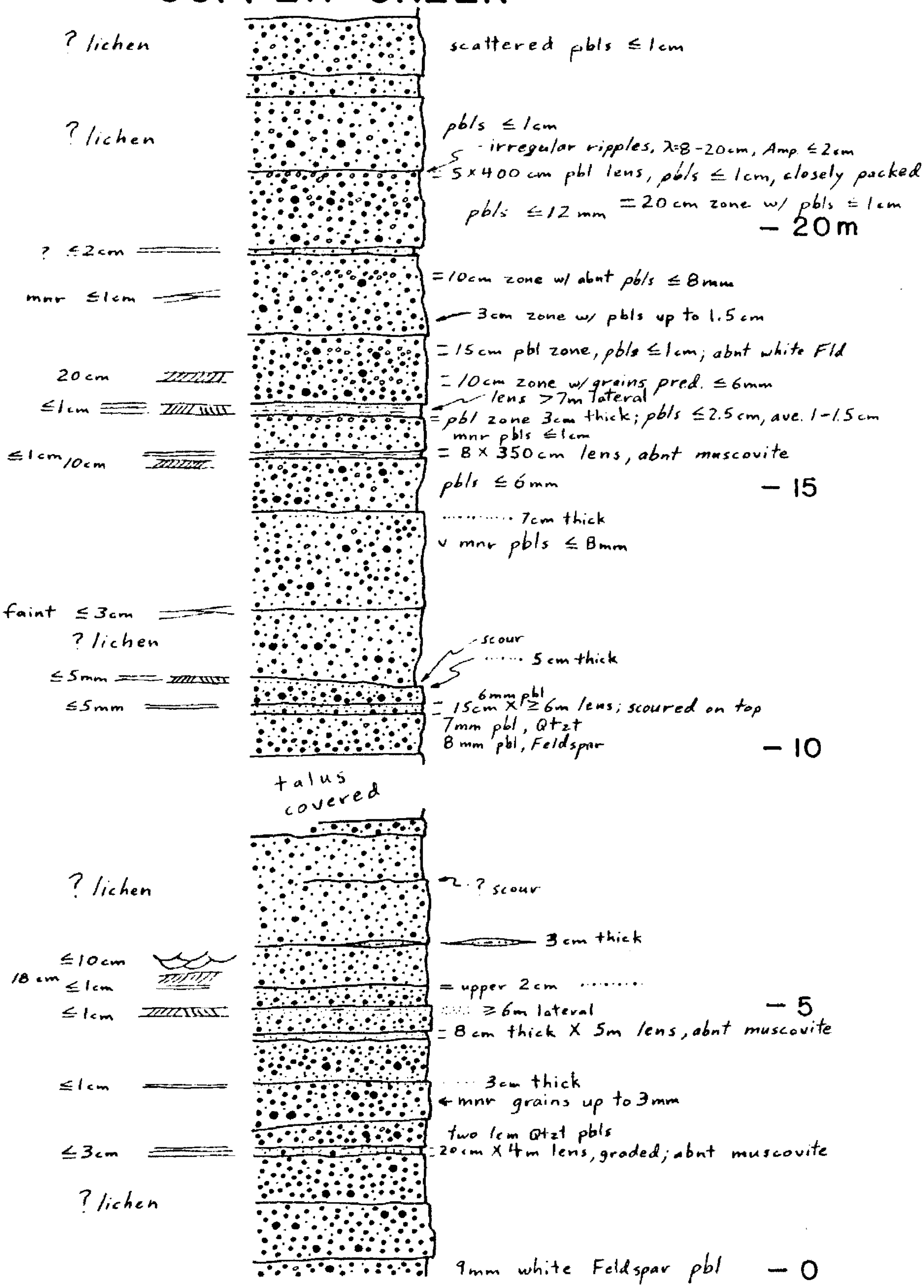


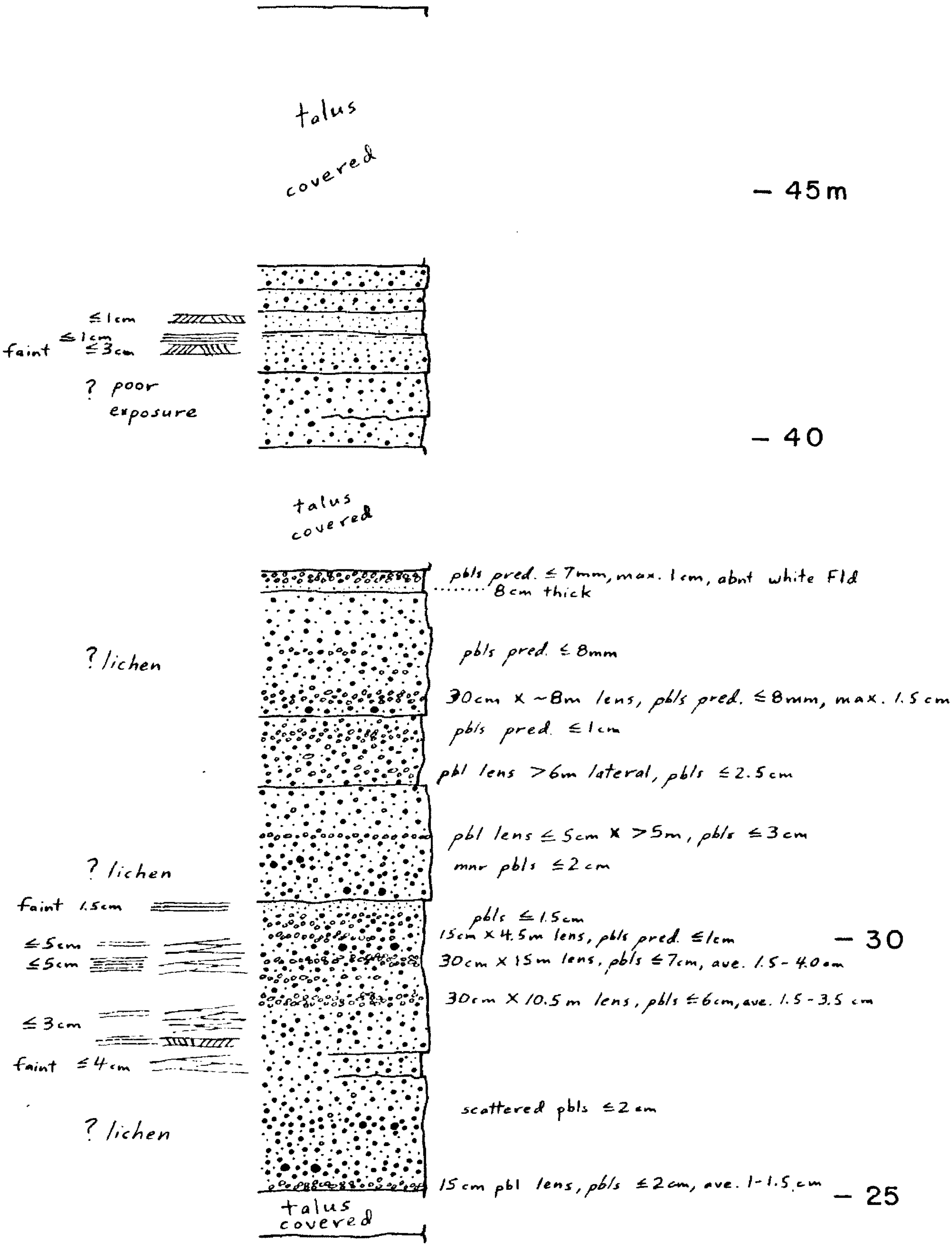
– 120 m
– 115
– 110
– 105
– 100
pbls ≤ 5 mm
pbls ≤ 5 mm
pbls ≤ 5 mm
? scour
13 cm thick
10 cm thick
7 cm thick
? lichen
? lichen
? lichen
? lichen

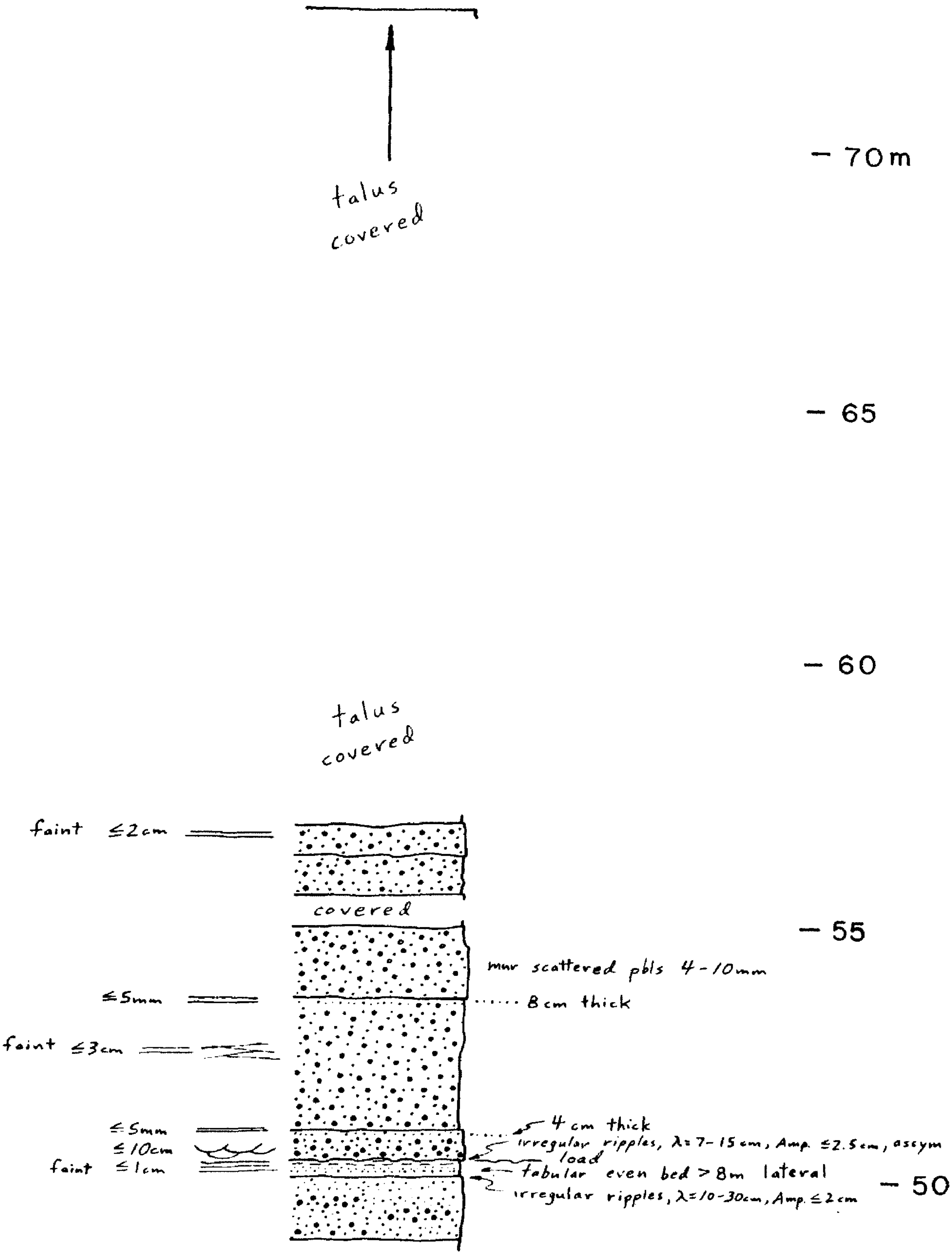

? lichen
≤ 2 cm
≤ 2 cm
mnr ≤ 3 cm
mnr ≤ 4 cm
— 140 m
≤ 1.5 cm ?
? lichen
≤ 1 cm mnr
≤ 2 cm mnr
— 135
?
≤ 2 cm
?
? lichen
? lichen
?
≤ 1.5 cm
≤ 2 cm
≤ 1.5 cm
— 130
mnr ≤ 2 cm
mnr ≤ 2 cm
3-6 cm mnr
≤ 2 cm
?
2-6 cm
≤ 2 cm
3-5 cm mnr
7 cm
— 125
?
faint 1-4 cm
faint ≤ 2 cm
? lichen
≤ 2 cm
mnr ≤ 2 cm
≤ 1 cm
≤ 2 cm


≤8 cm
≤3cm
≤3cm
≤2cm
≤5cm
— 145 m

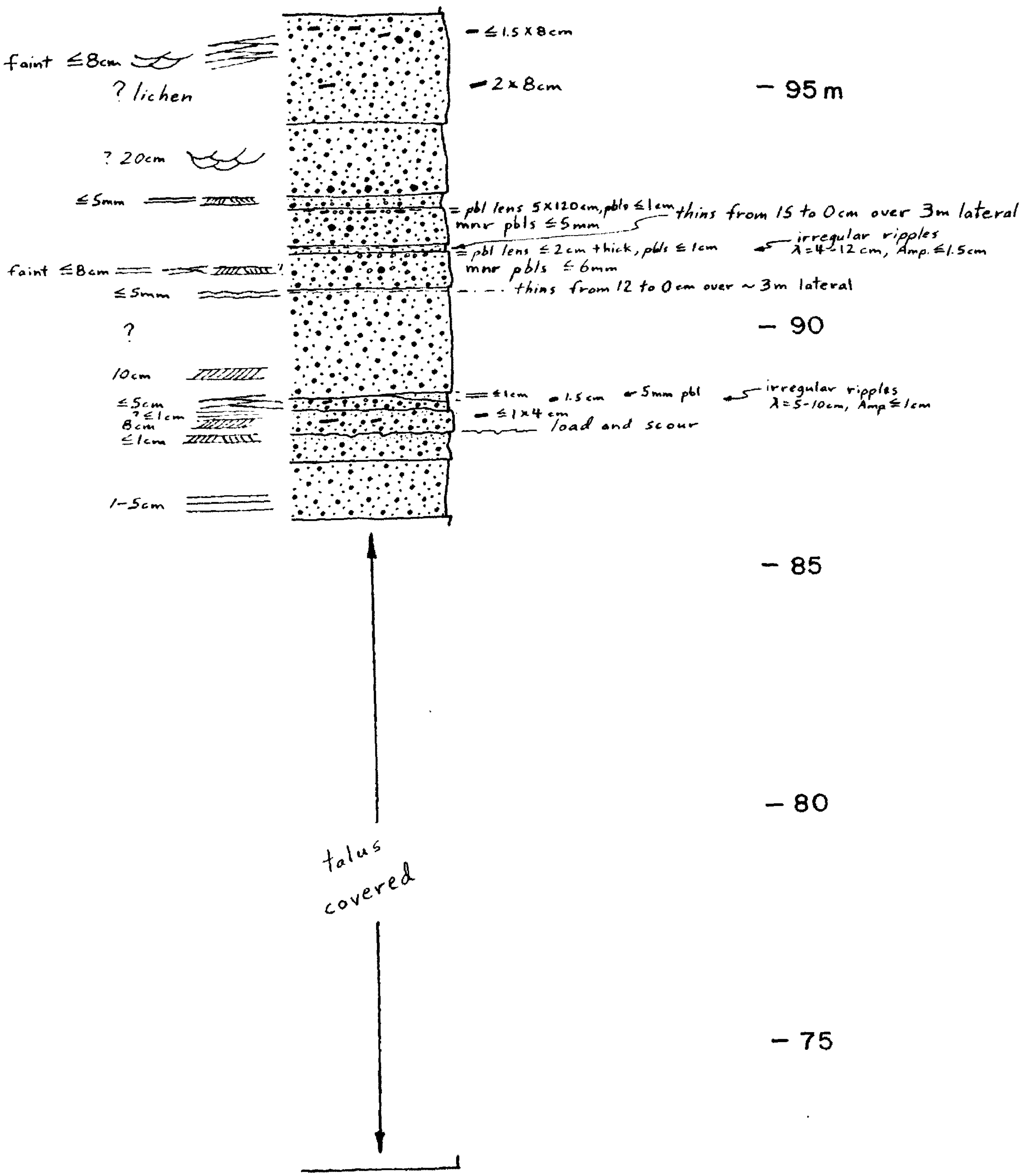
COPPER CREEK

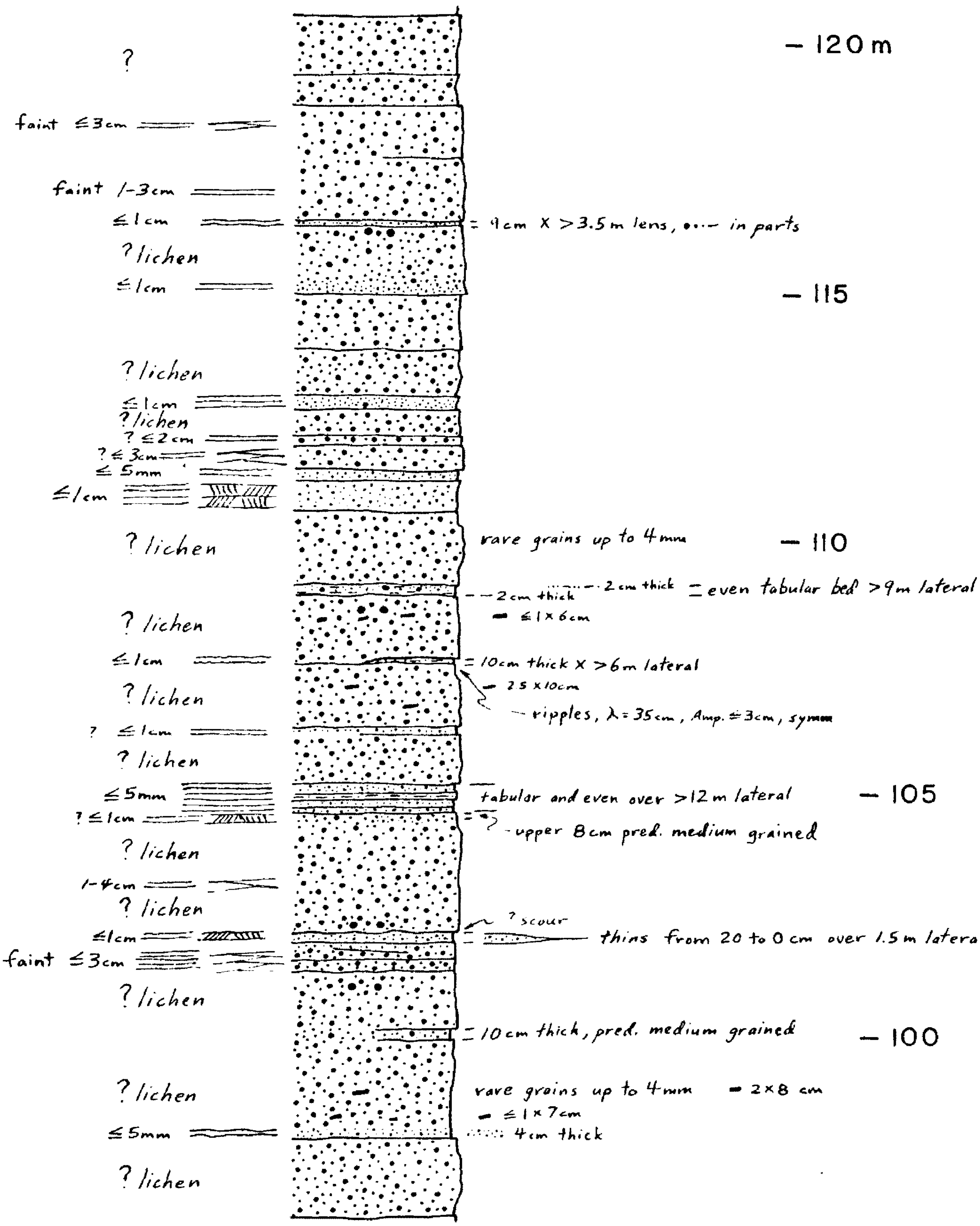



talus
covered
– 45m
≤1cm
≤1cm
faint ≤3cm
? poor exposure
– 40
talus
covered
pbls pred. ≤7mm, max. 1cm, abnt white Fld
8cm thick
? lichen
pbls pred. ≤8mm
30cm × ~8m lens, pbls pred. ≤8mm, max. 1.5cm
pbls pred. ≤1cm
pbl lens >6m lateral, pbls ≤2.5cm
pbl lens ≤5cm × >5m, pbls ≤3cm
? lichen
mnr pbls ≤2cm
faint 1.5cm
pbls ≤1.5cm
≤5cm
15cm × 4.5m lens, pbls pred. ≤1cm
– 30
≤5cm
30cm × 15m lens, pbls ≤7cm, ave. 1.5-4.0cm
30cm × 10.5m lens, pbls ≤6cm, ave. 1.5-3.5cm
≤3cm
faint ≤4cm
scattered pbls ≤2cm
? lichen
15cm pbl lens, pbls ≤2cm, ave. 1-1.5cm
– 25
talus
covered

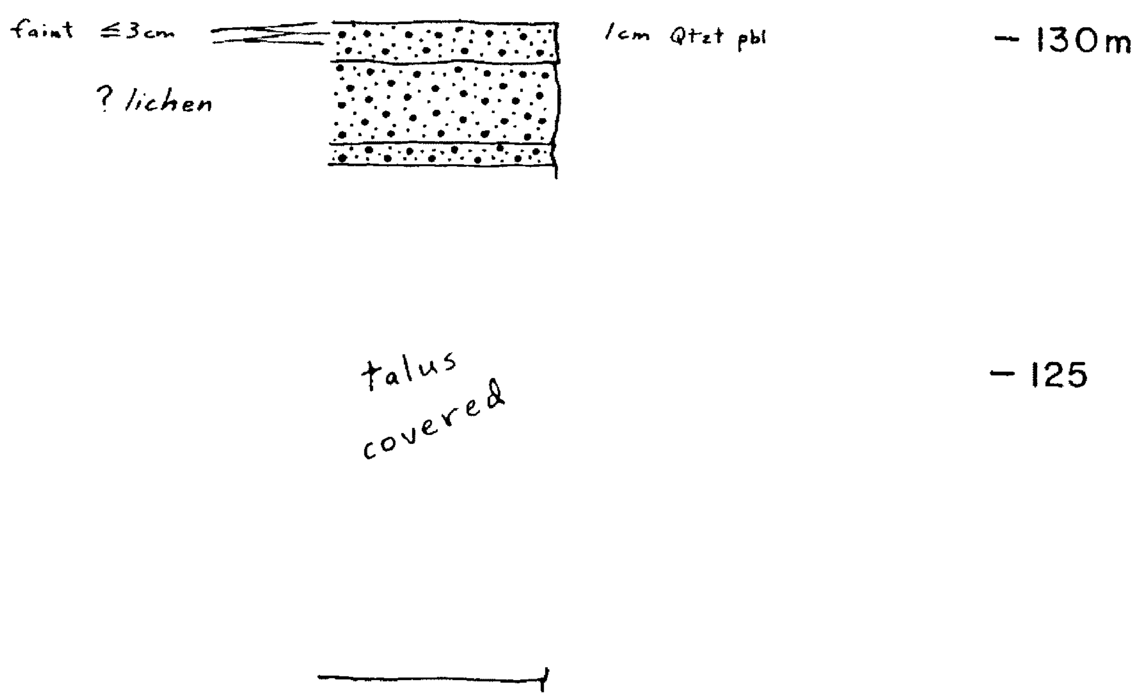


talus covered
– 70m
– 65
– 60
talus covered
faint ≤2cm
covered
– 55
mnr scattered pbls 4-10mm
≤5mm
8 cm thick
faint ≤3cm
≤5mm
≤10cm
faint ≤1cm
4 cm thick
irregular ripples, λ= 7-15 cm, Amp. ≤2.5cm, ascym
load
tabular even bed > 8m lateral
irregular ripples, λ=10-30cm, Amp. ≤2cm
– 50


faint ≤8cm
? lichen
? 20cm
≤5mm
faint ≤8cm
≤5mm
?
10cm
≤5cm
? ≤1cm
8cm
≤1cm
1-5cm
≤1.5 x 8cm
2 x 8cm
pbl lens 5x120cm, pbls ≤1cm thins from 15 to 0cm over 3m lateral
mnr pbls ≤5mm
pbl lens ≤2cm thick, pbls ≤1cm
irregular ripples λ=4-12cm, Amp. ≤1.5cm
mnr pbls ≤6mm
thins from 12 to 0cm over ~3m lateral
≤1cm
1.5cm
5mm pbl
irregular ripples λ=5-10cm, Amp ≤1cm
≤1x4cm
load and scour
talus covered
95 m
90
85
80
75

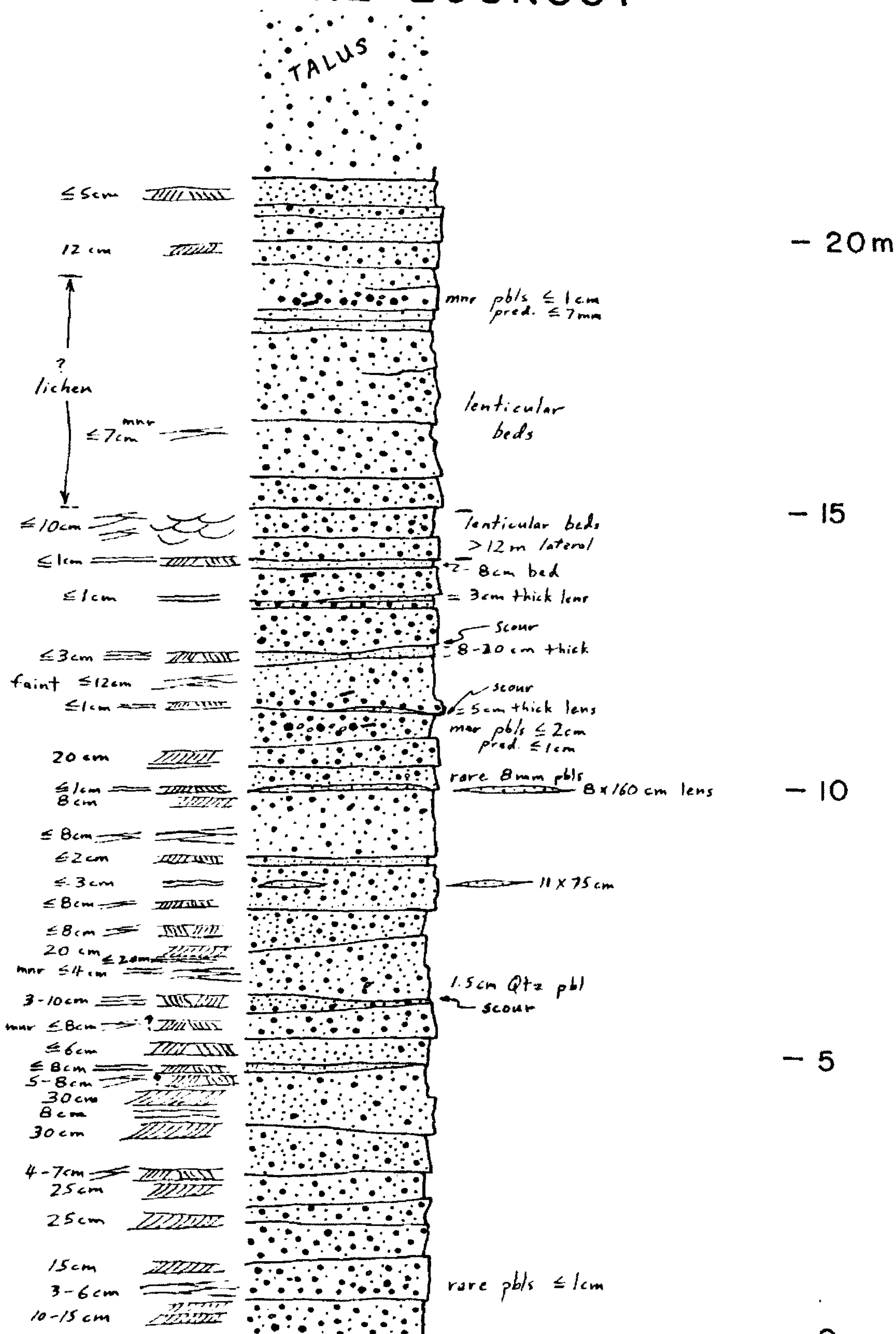


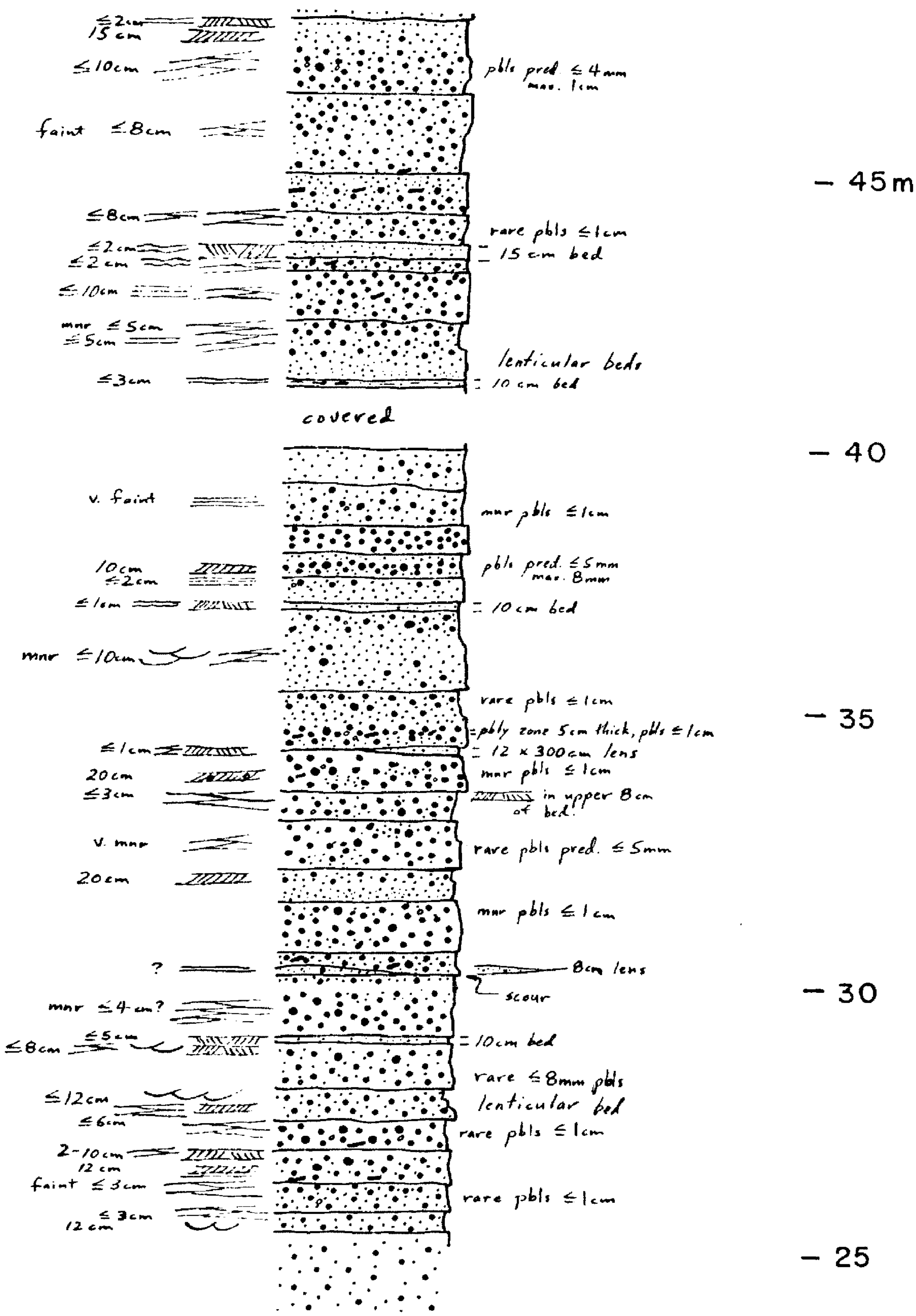
— 120 m
?
faint ≤3cm
faint 1-3cm
≤1cm
= 9cm X >3.5m lens, in parts
? lichen
≤1cm
— 115
? lichen
≤1cm
? lichen
? ≤2cm
? ≤3cm
≤5mm
≤1cm
? lichen
rare grains up to 4mm
— 110
2cm thick
2cm thick
= even tabular bed >9m lateral
≤1×6cm
? lichen
≤1cm
= 10cm thick X >6m lateral
25×10cm
? lichen
ripples, λ = 35cm, Amp. ≤ 3cm, symm
? ≤1cm
? lichen
≤5mm
tabular and even over >12m lateral
— 105
? ≤1cm
upper 8cm pred. medium grained
? lichen
1-4cm
? lichen
? scour
≤1cm
thins from 20 to 0 cm over 1.5m lateral
faint ≤3cm
? lichen
= 10cm thick, pred. medium grained
— 100
? lichen
rare grains up to 4mm
2×8 cm
≤1×7cm
≤5mm
4cm thick
? lichen

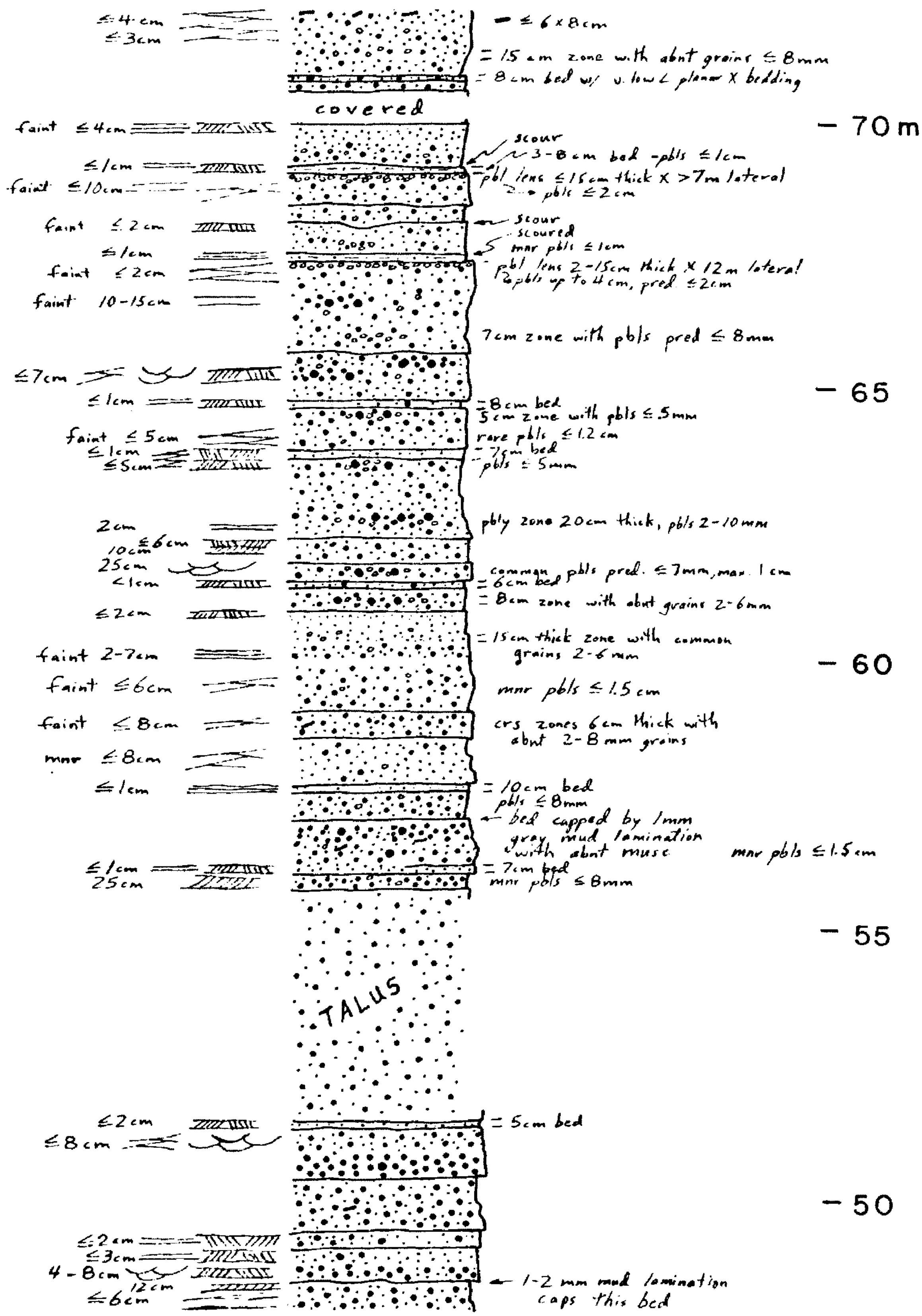


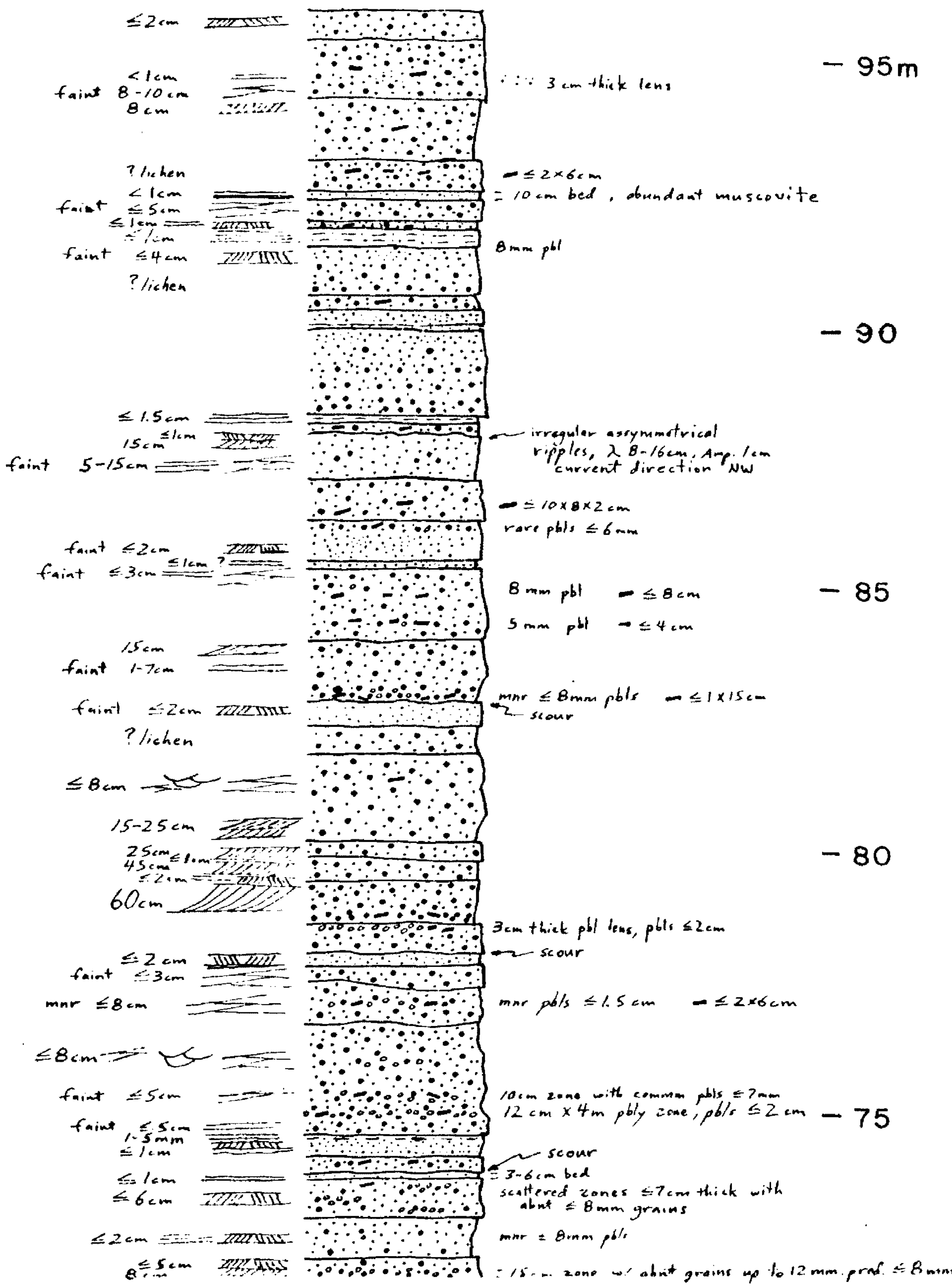
faint ≤3cm
? lichen
1cm Qtzt pbl
— 130m
— 125
talus covered

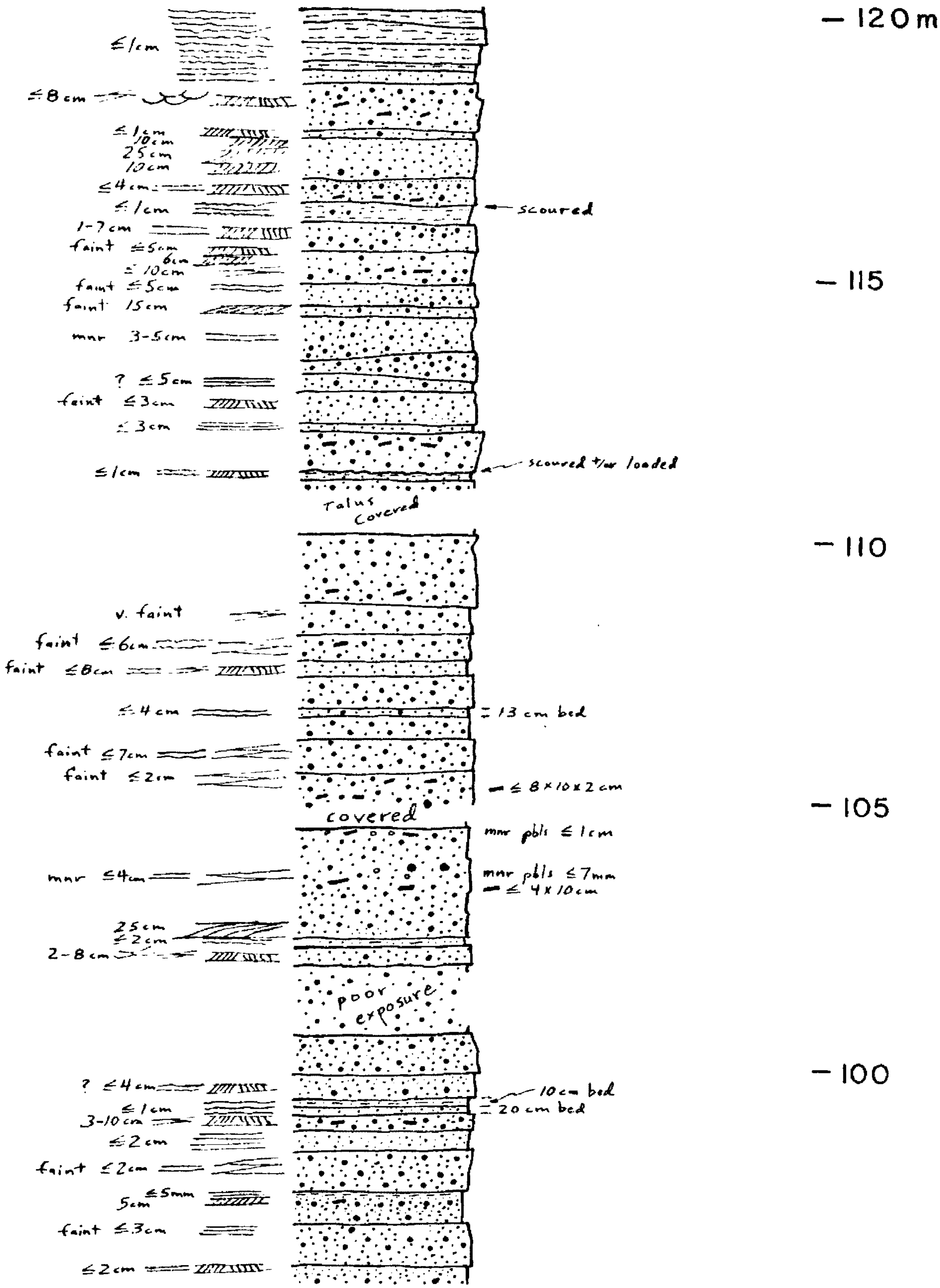
EMERINE LOOKOUT

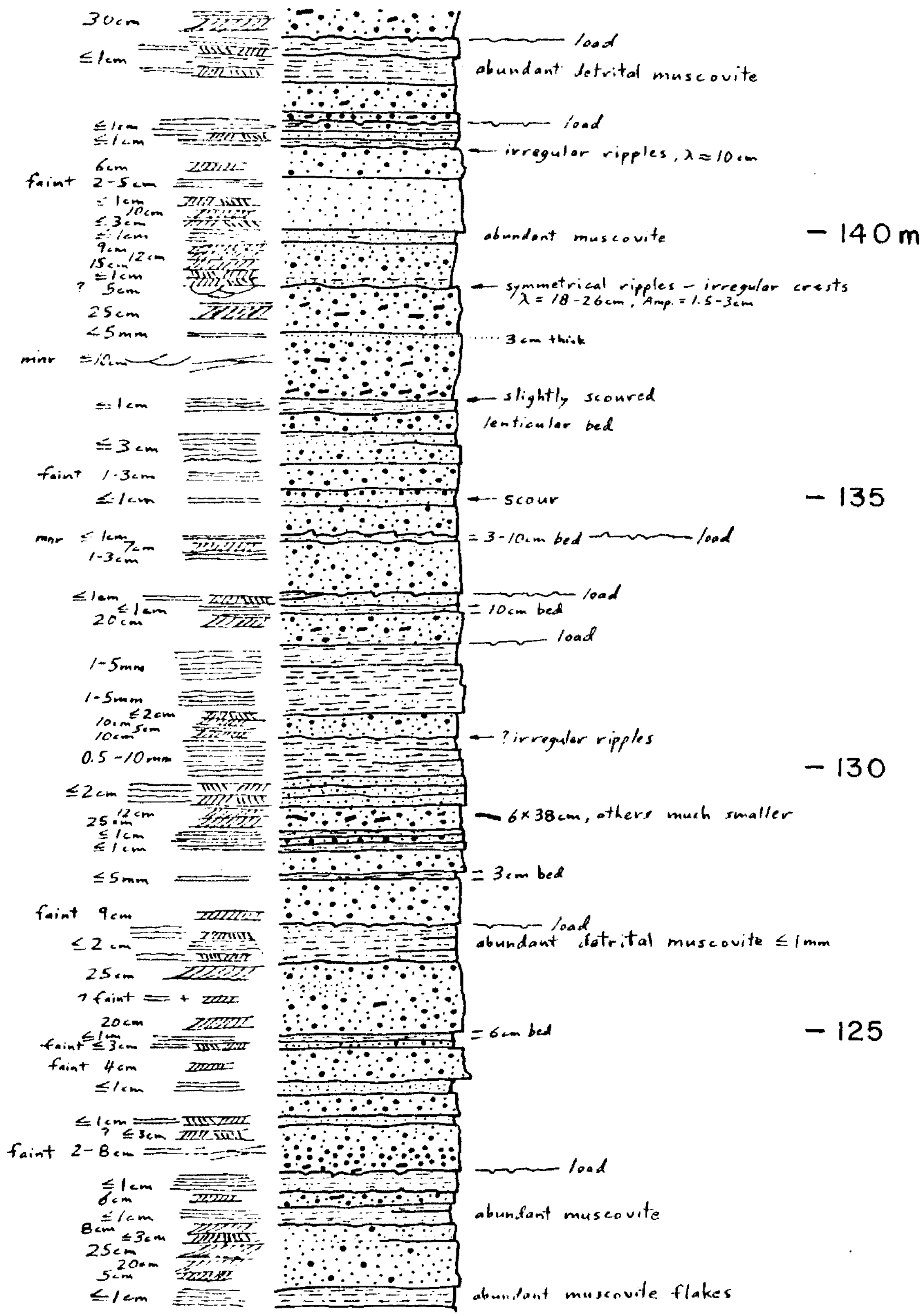


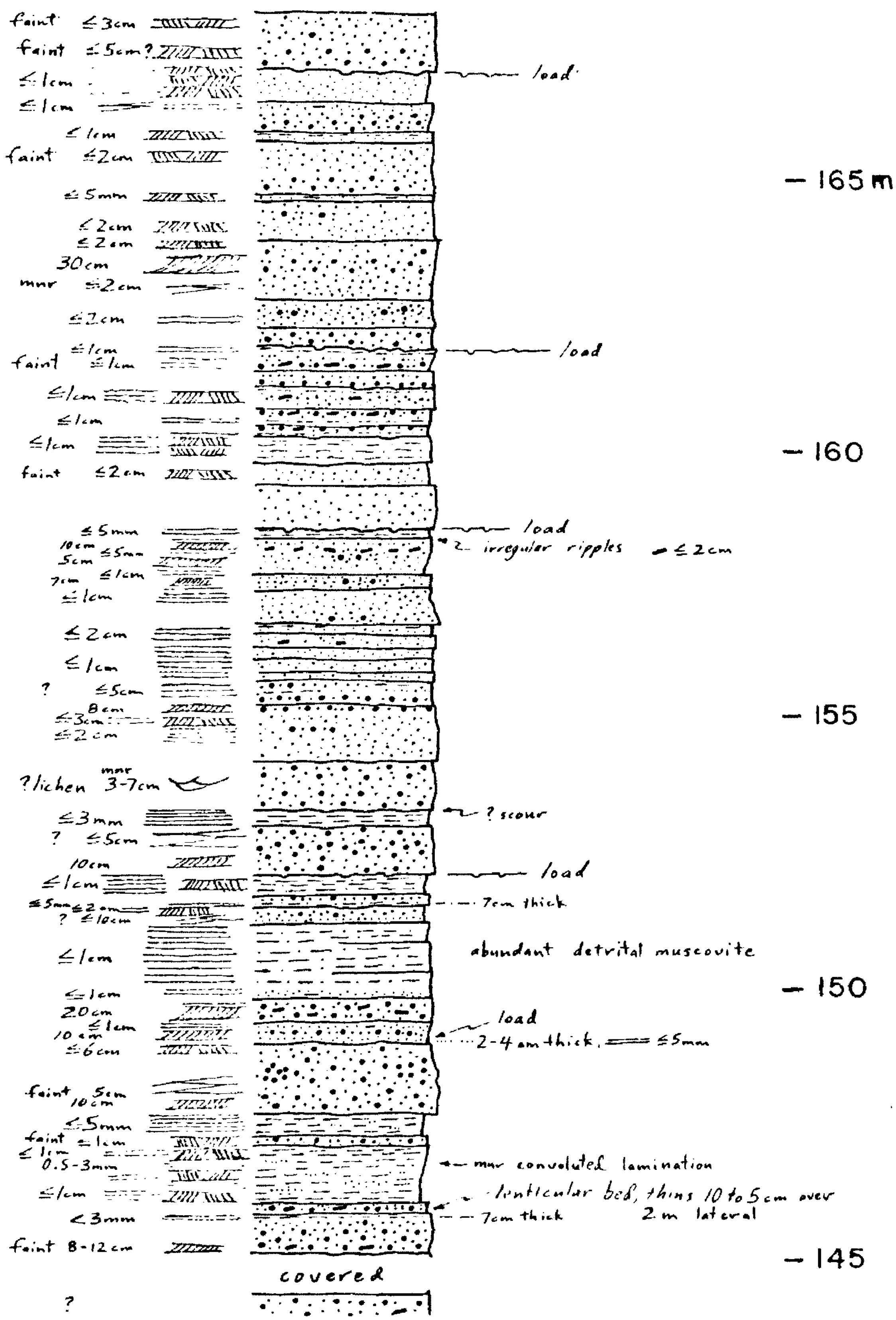

≤2cm
15 cm
≤10cm
pbls pred ≤ 4mm max. 1cm
faint ≤8cm
– 45m
≤8cm
rare pbls ≤1cm
≤2cm
≤2 cm
15 cm bed
≤10cm
mnr ≤5cm
≤5cm
lenticular beds
≤3cm
10 cm bed
covered
– 40
v. faint
mnr pbls ≤1cm
10cm
≤2cm
pbls pred. ≤5mm max. 8mm
≤1cm
10cm bed
mnr ≤10cm
rare pbls ≤1cm
– 35
pbly zone 5cm thick, pbls ≤1cm
≤1cm
12 × 300cm lens
20cm
mnr pbls ≤1cm
≤3cm
in upper 8cm of bed
v. mnr
rare pbls pred. ≤5mm
20cm
mnr pbls ≤1cm
?
8cm lens
scour
– 30
mnr ≤4cm?
≤5cm
≤8cm
10cm bed
rare ≤8mm pbls
≤12cm
lenticular bed
≤6cm
rare pbls ≤1cm
2-10cm
12 cm
faint ≤3cm
rare pbls ≤1cm
≤3cm
12 cm
– 25

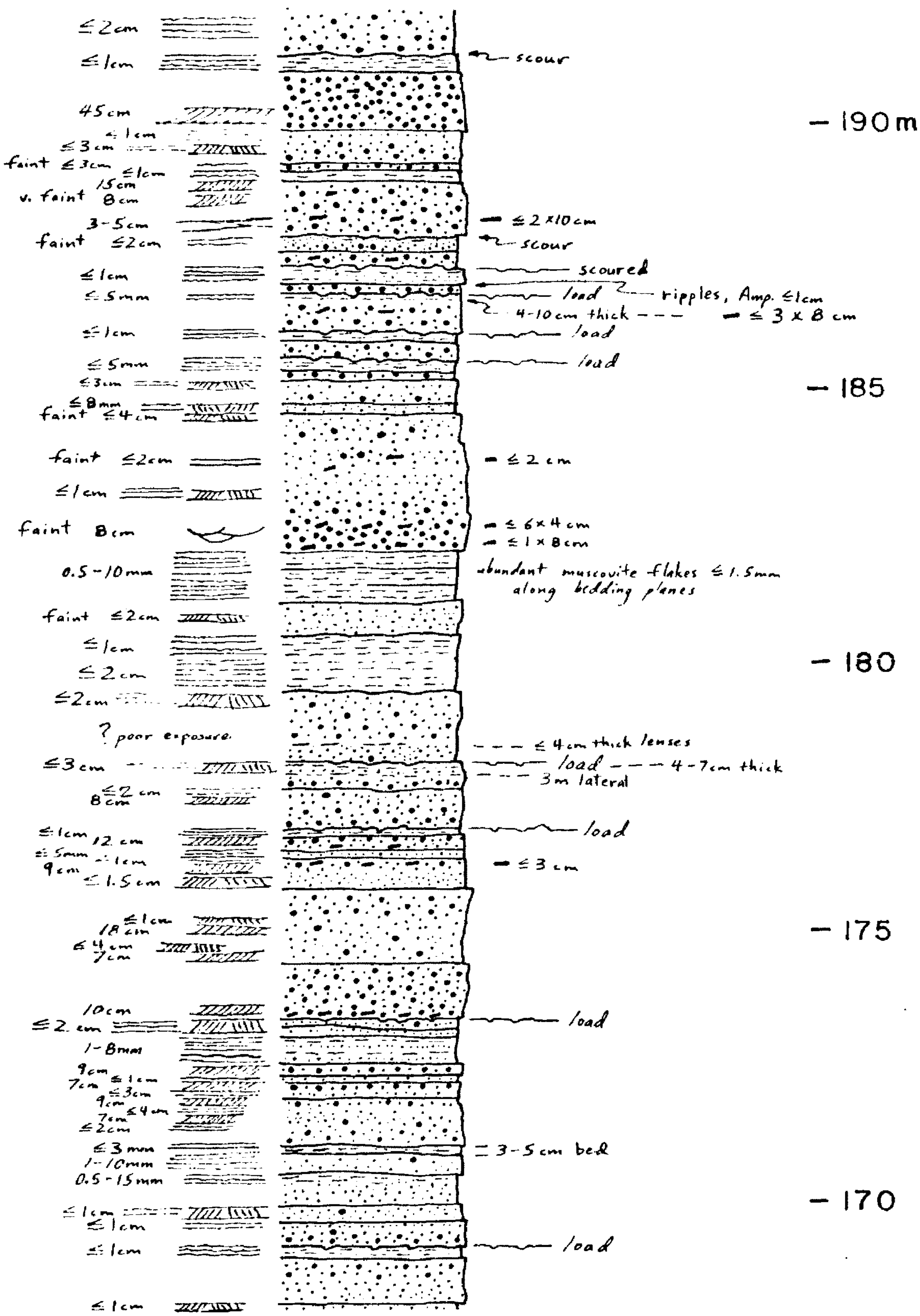

≤ 6 x 8 cm
≤ 15 cm zone with abnt grains ≤ 8mm
≤ 8 cm bed w/ v. low ∠ planar X bedding
covered
– 70m
scour
3-8 cm bed - pbls ≤ 1cm
pbl lens ≤ 15 cm thick X > 7m lateral
pbls ≤ 2 cm
scour
scoured
mnr pbls ≤ 1cm
pbl lens 2-15cm thick X 12 m lateral
pbls up to 4 cm, pred ≤ 2cm
7cm zone with pbls pred ≤ 8mm
– 65
≤ 8 cm bed
5 cm zone with pbls ≤ 5mm
rare pbls ≤ 1.2 cm
7cm bed
pbls ≤ 5mm
pbly zone 20cm thick, pbls 2-10mm
common pbls pred. ≤ 7mm, max. 1 cm
≤ 6cm bed
≤ 8cm zone with abnt grains 2-6mm
≤ 15cm thick zone with common grains 2-6 mm
– 60
mnr pbls ≤ 1.5 cm
crs zones 6cm thick with abnt 2-8 mm grains
≤ 10cm bed
pbls ≤ 8mm
bed capped by 1mm grey mud lamination with abnt musc
mnr pbls ≤ 1.5cm
≤ 7cm bed
mnr pbls ≤ 8mm
– 55
TALUS
≤ 5cm bed
– 50
1-2 mm mud lamination caps this bed
≤ 4 cm
≤ 3cm
faint ≤ 4cm
≤ 1cm
faint ≤ 10cm
faint ≤ 2 cm
≤ 1cm
faint ≤ 2cm
faint 10-15cm
≤ 7cm
≤ 1cm
faint ≤ 5cm
≤ 1cm
≤ 5cm
2cm
10cm ≤ 6cm
25cm
< 1cm
≤ 2cm
faint 2-7cm
faint ≤ 6cm
faint ≤ 8cm
mnr ≤ 8cm
≤ 1cm
≤ 1cm
25cm
≤ 2cm
≤ 8 cm
≤ 2 cm
≤ 3cm
4 - 8cm
12cm
≤ 6cm


95m
90
85
80
75
3 cm thick lens
≤ 2×6 cm
10 cm bed, abundant muscovite
8 mm pbl
irregular asymmetrical ripples, λ 8-16 cm, Amp. 1 cm current direction NW
≤ 10×8×2 cm
rare pbls ≤ 6 mm
8 mm pbl ≤ 8 cm
5 mm pbl ≤ 4 cm
mnr ≤ 8 mm pbls ≤ 1×15 cm
scour
3 cm thick pbl lens, pbls ≤ 2 cm
scour
mnr pbls ≤ 1.5 cm ≤ 2×6 cm
10 cm zone with common pbls ≤ 7 mm
12 cm × 4 m pbly zone, pbls ≤ 2 cm
scour
3-6 cm bed
scattered zones ≤ 7 cm thick with abnt ≤ 8 mm grains
mnr ≤ 8 mm pbls
15 cm zone w/ abnt grains up to 12 mm, prdt ≤ 8 mm
≤ 2 cm
< 1 cm
faint 8-10 cm
8 cm
? lichen
< 1 cm
faint ≤ 5 cm
≤ 1 cm
< 1 cm
faint ≤ 4 cm
? lichen
≤ 1.5 cm
15 cm ≤ 1 cm
faint 5-15 cm
faint ≤ 2 cm
faint ≤ 3 cm ≤ 1 cm ?
15 cm
faint 1-7 cm
faint ≤ 2 cm
? lichen
≤ 8 cm
15-25 cm
25 cm ≤ 1 cm
45 cm
≤ 2 cm
60 cm
≤ 2 cm
faint ≤ 3 cm
mnr ≤ 8 cm
≤ 8 cm
faint ≤ 5 cm
faint ≤ 5 cm
1-5 mm
≤ 1 cm
≤ 1 cm
≤ 6 cm
≤ 2 cm
8 ≤ 5 cm

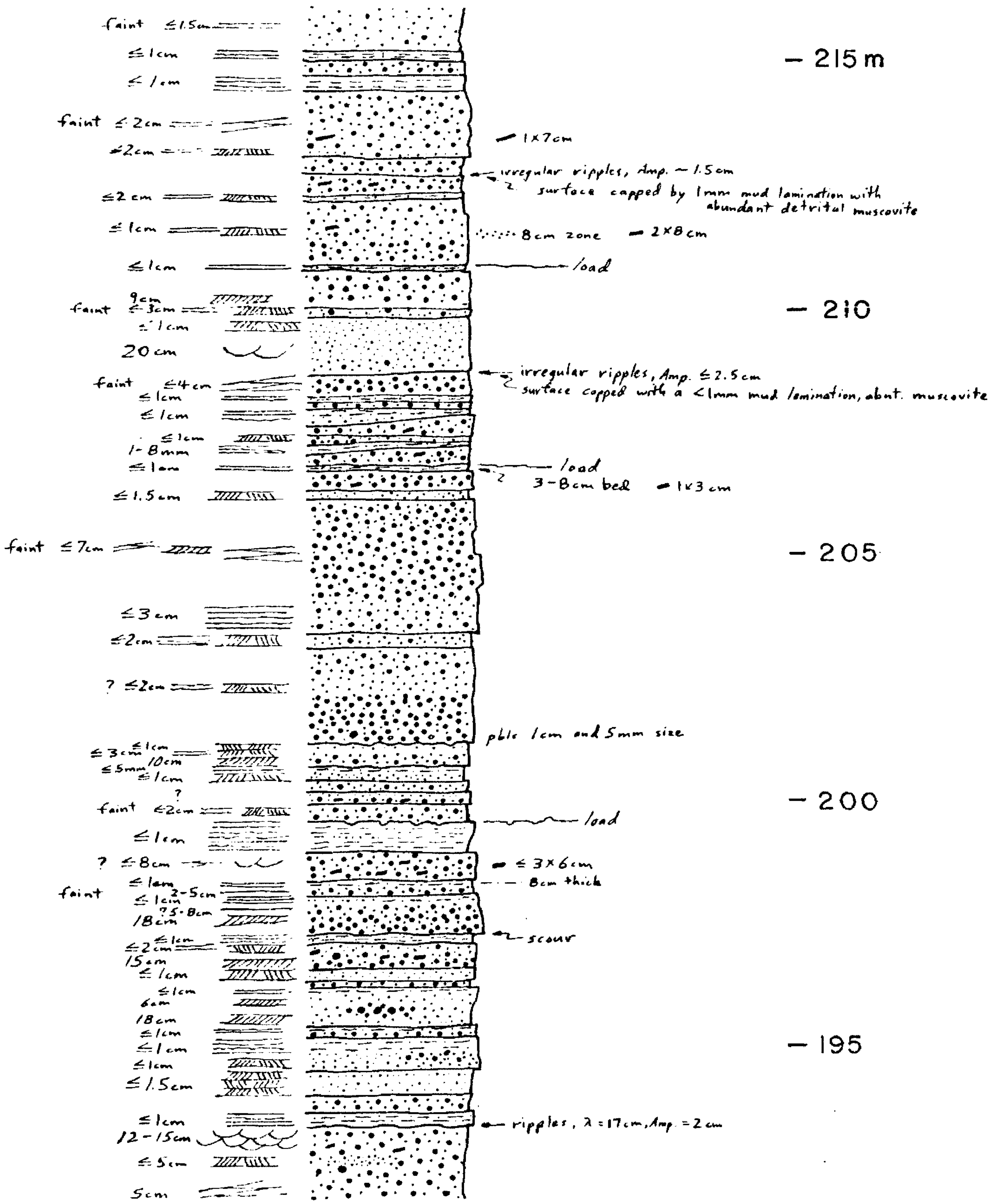

120m
115
110
105
100
scoured
scoured +/or loaded
Talus covered
covered
poor exposure
13 cm bed
10 cm bed
20 cm bed
≤ 8×10×2 cm
mnr pbls ≤ 1cm
mnr pbls ≤ 7mm
≤ 4×10cm
≤1cm
≤8cm
≤4cm
1-7cm
faint ≤5cm
faint 15cm
mnr 3-5cm
? ≤5cm
faint ≤3cm
v. faint
faint ≤6cm
faint ≤8cm
≤4cm
faint ≤7cm
faint ≤2cm
mnr ≤4cm
25cm
≤2cm
2-8cm
? ≤4cm
3-10cm
≤2cm
faint ≤2cm
≤5mm
5cm
faint ≤3cm
≤2cm


30cm
≤1cm
load
abundant detrital muscovite
load
irregular ripples, λ ≈ 10cm
6cm
faint 2-5cm
abundant muscovite
— 140m
symmetrical ripples – irregular crests
λ = 18-26cm, Amp. = 1.5-3cm
25cm
≤5mm
3cm thick
slightly scoured
lenticular bed
≤3cm
faint 1-3cm
scour
— 135
= 3-10cm bed
load
load
= 10cm bed
20cm
load
1-5mm
1-5mm
? irregular ripples
0.5-10mm
— 130
≤2cm
6×38cm, others much smaller
≤5mm
= 3cm bed
faint 9cm
load
abundant detrital muscovite ≤1mm
25cm
? faint
20cm
= 6cm bed
— 125
faint 4cm
faint 2-8cm
load
abundant muscovite
25cm
abundant muscovite flakes

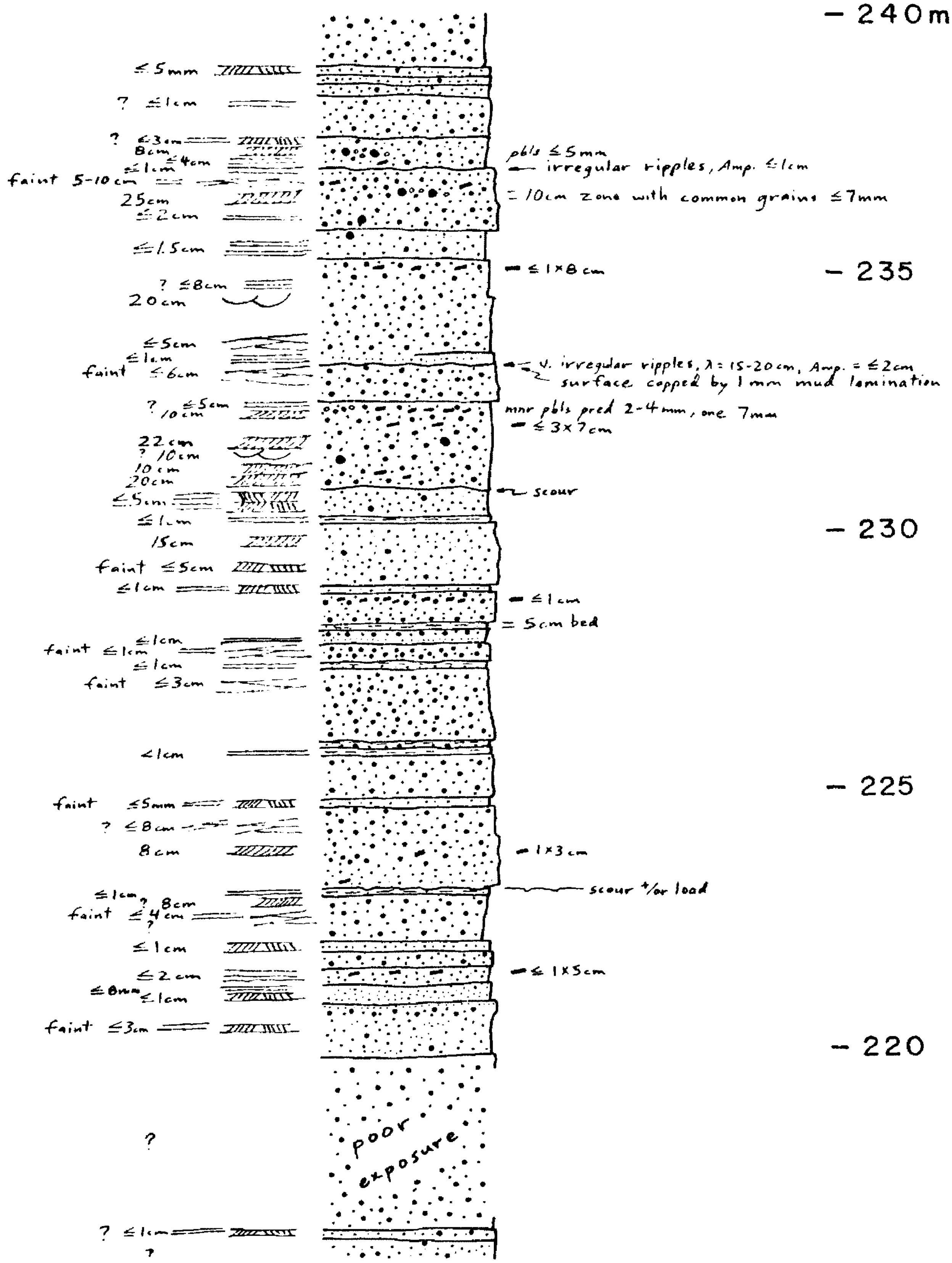

load
load
load
irregular ripples ≤ 2cm
? scour
load
7cm thick
abundant detrital muscovite
load
2-4 cm thick, ≤ 5mm
mnr convoluted lamination
lenticular bed, thins 10 to 5 cm over 2 m lateral
7cm thick
covered
– 165 m
– 160
– 155
– 150
– 145
?lichen
faint



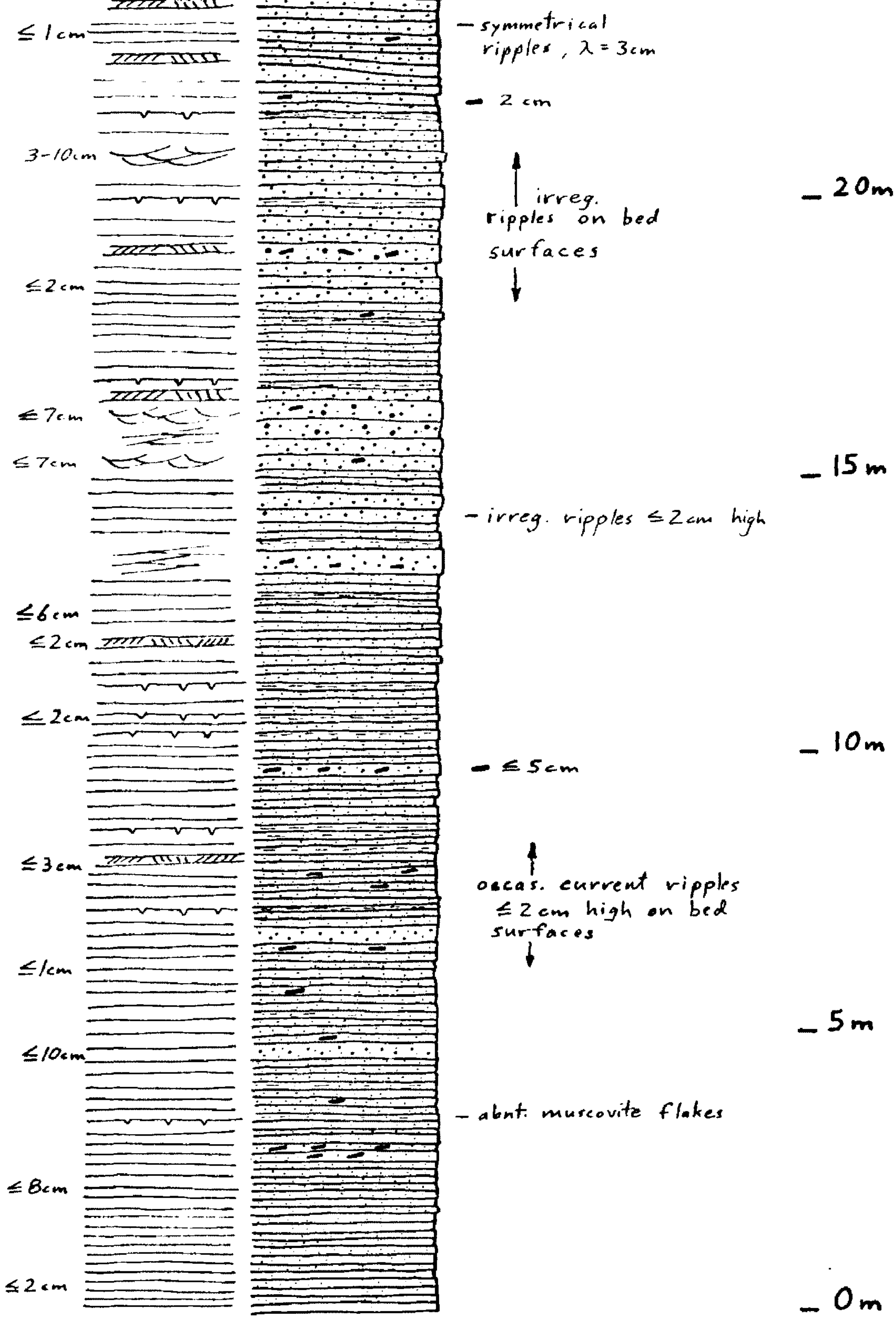
scour
190m
≤ 2 x 10 cm
scour
scoured
load
ripples, Amp. ≤1cm
4-10 cm thick
≤ 3 x 8 cm
load
load
185
≤ 2 cm
≤ 6 x 4 cm
≤ 1 x 8 cm
abundant muscovite flakes ≤ 1.5mm along bedding planes
180
? poor exposure
≤ 4 cm thick lenses
load
4-7cm thick
3m lateral
load
≤ 3 cm
175
load
3-5 cm bed
170
load

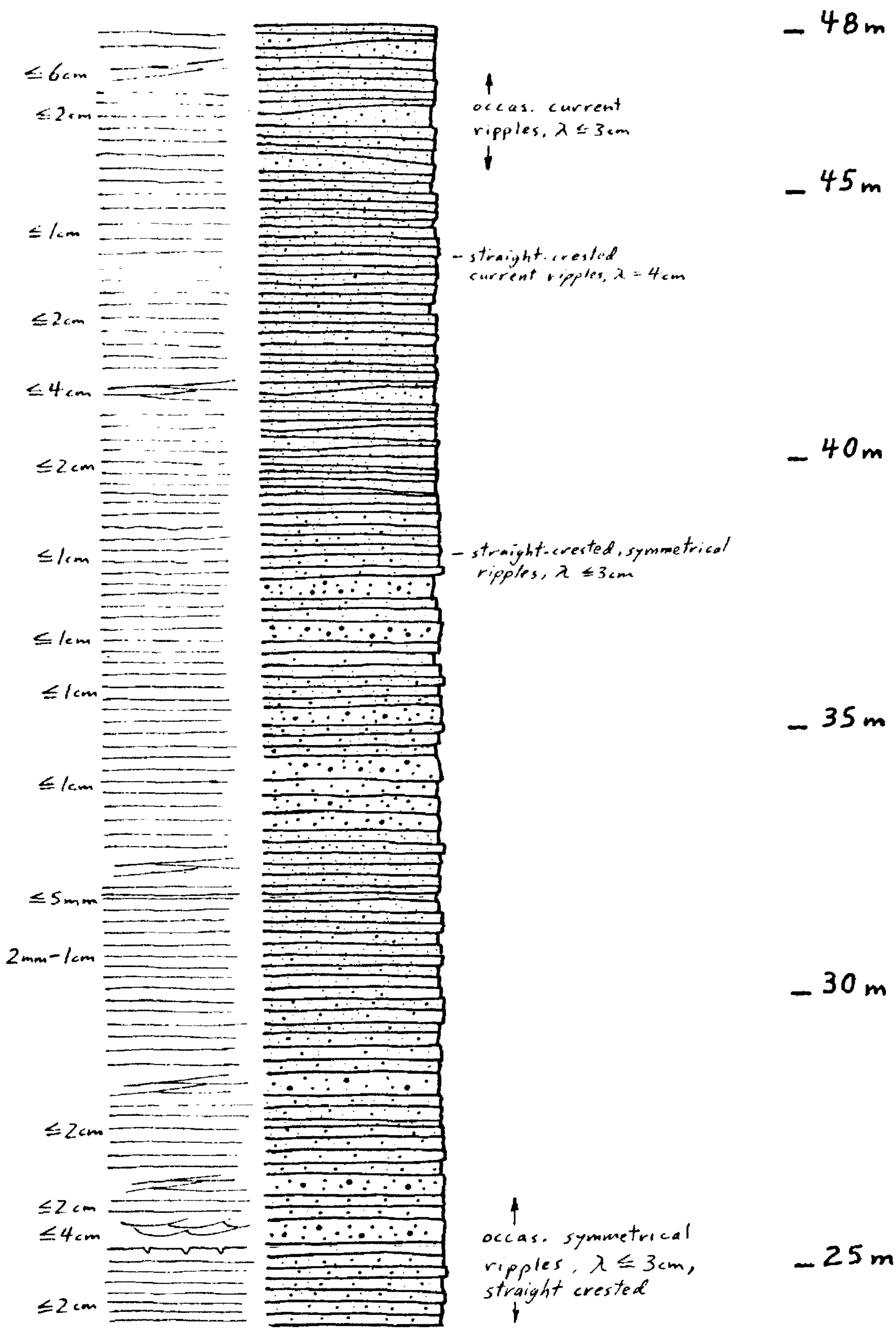


215 m
210
205
200
195
1x7cm
irregular ripples, Amp. ~ 1.5 cm
surface capped by 1mm mud lamination with abundant detrital muscovite
8cm zone
2x8cm
load
irregular ripples, Amp. ≤ 2.5 cm
surface capped with a <1mm mud lamination, abnt. muscovite
load
3-8cm bed
1x3 cm
pble 1cm and 5mm size
load
≤ 3x6cm
8cm thick
scour
ripples, λ = 17cm, Amp. = 2 cm

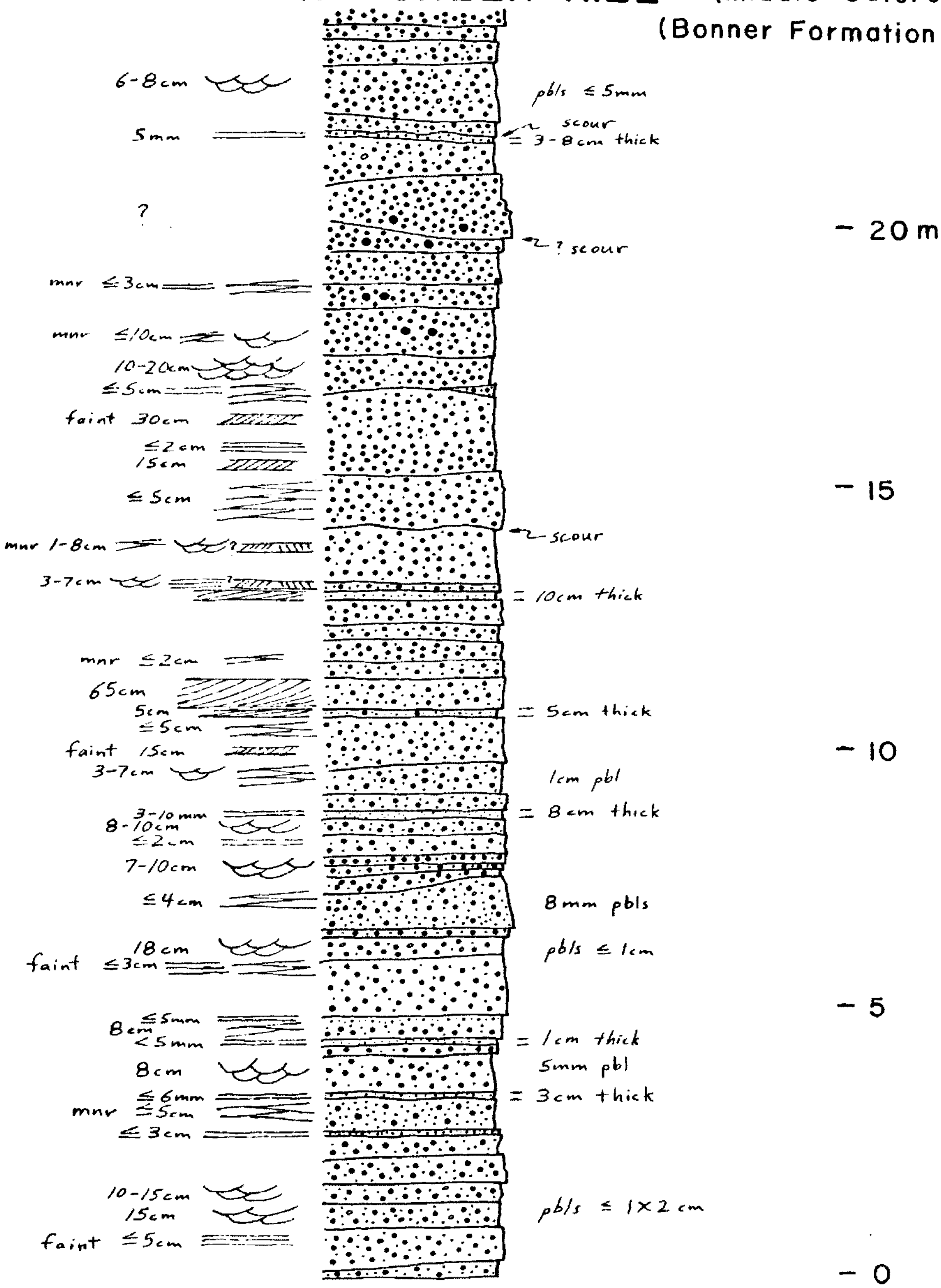

240m
235
230
225
220
pbls ≤ 5mm
irregular ripples, Amp. ≤ 1cm
≤ 10cm zone with common grains ≤ 7mm
≤ 1×8 cm
v. irregular ripples, λ = 15-20cm, Amp. = ≤ 2cm
surface capped by 1mm mud lamination
mnr pbls pred 2-4mm, one 7mm
≤ 3×7cm
scour
≤ 1cm
≤ 5cm bed
1×3cm
scour +/or load
≤ 1×5cm
poor exposure
faint 5-10cm
faint
?

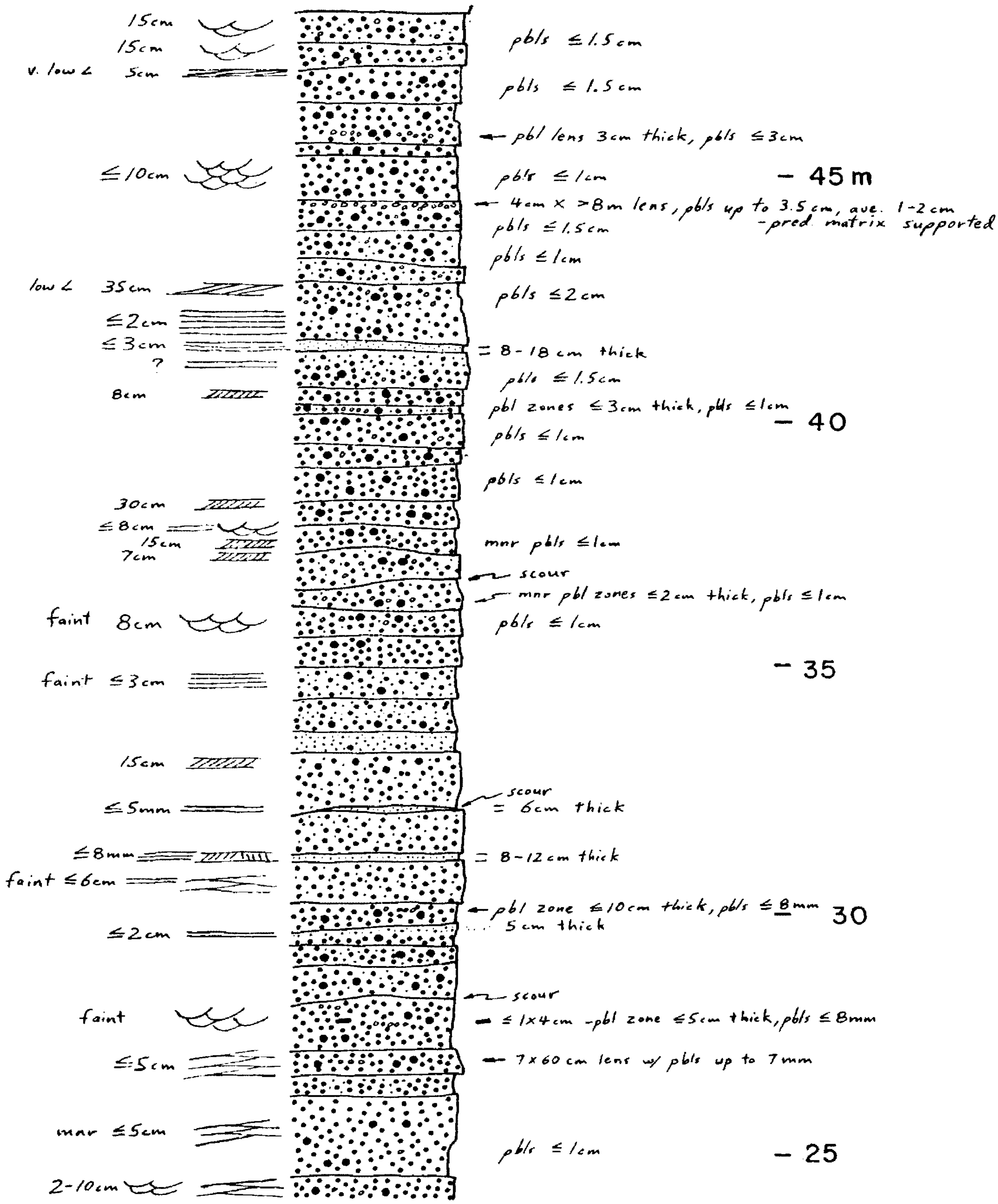
FLINT CREEK HILL (Lower Outcrop)
(Mount Shields Formation)



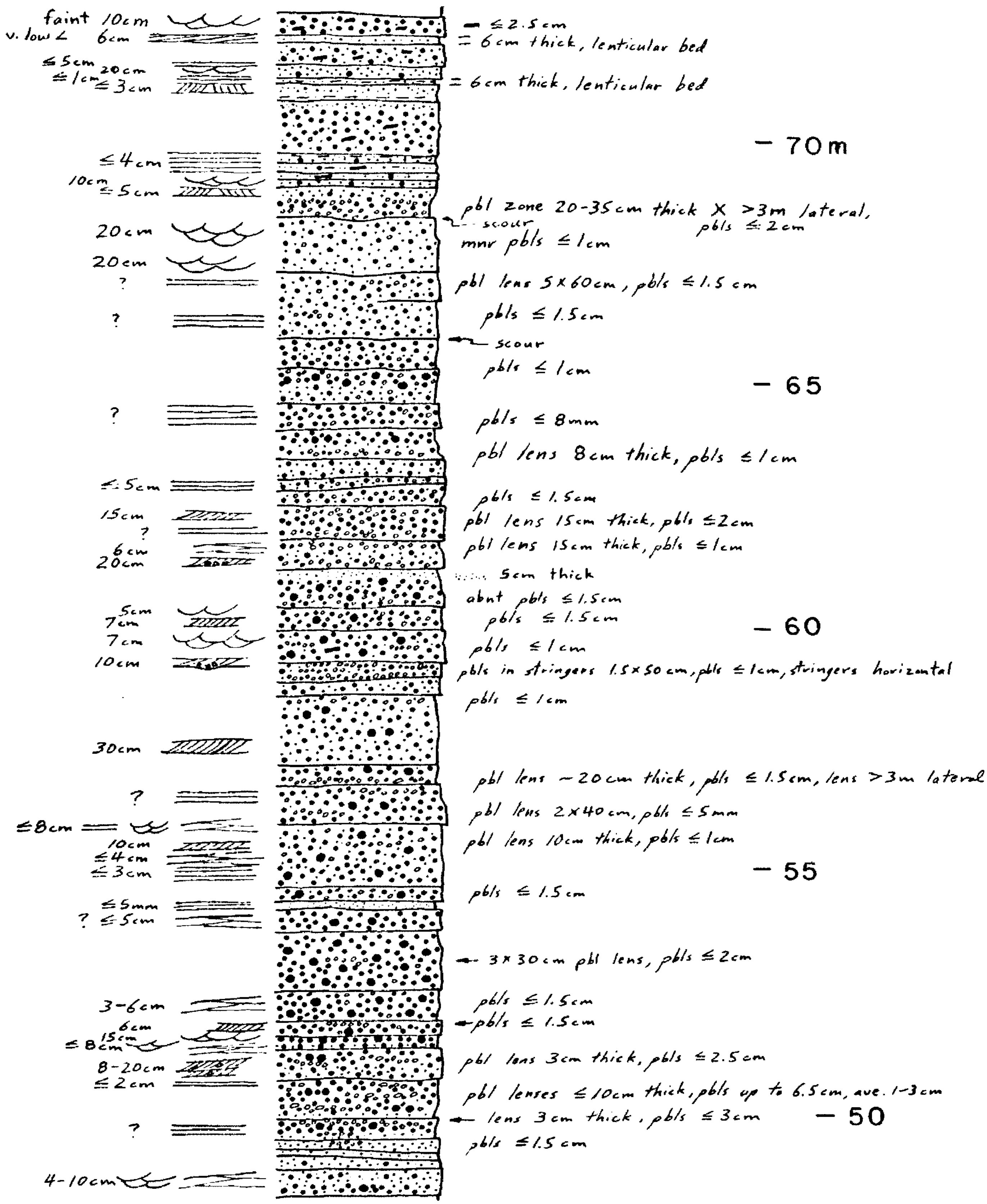

48m
≤6cm
≤2cm
occas. current ripples, λ ≤ 3cm
45m
≤1cm
straight-crested current ripples, λ = 4cm
≤2cm
≤4cm
40m
≤2cm
≤1cm
straight-crested, symmetrical ripples, λ ≤ 3cm
≤1cm
≤1cm
35m
≤1cm
≤5mm
2mm-1cm
30m
≤2cm
≤2cm
≤4cm
occas. symmetrical ripples, λ ≤ 3cm, straight crested
25m
≤2cm

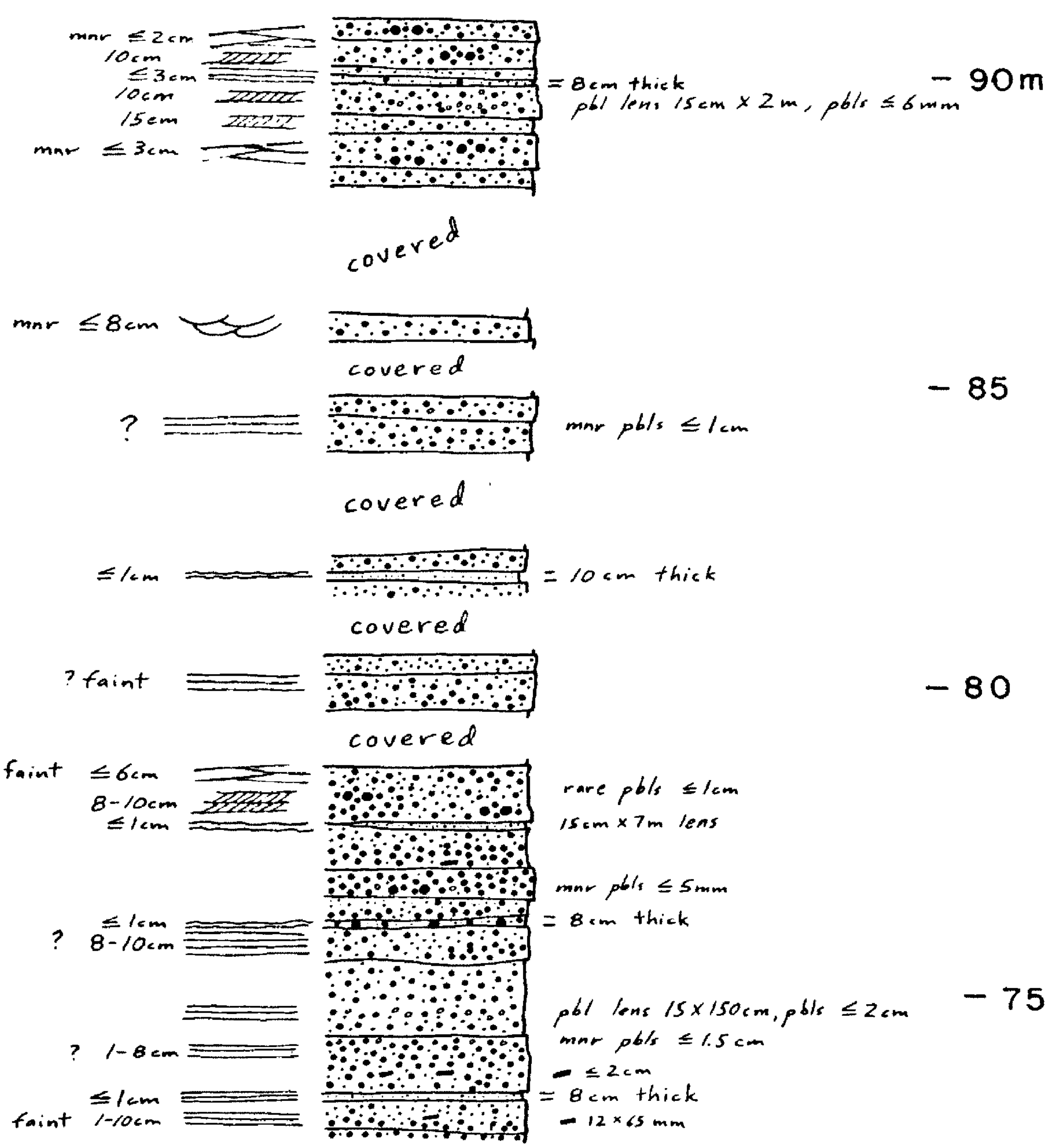
FLINT CREEK HILL (Middle Outcrop)
(Bonner Formation)



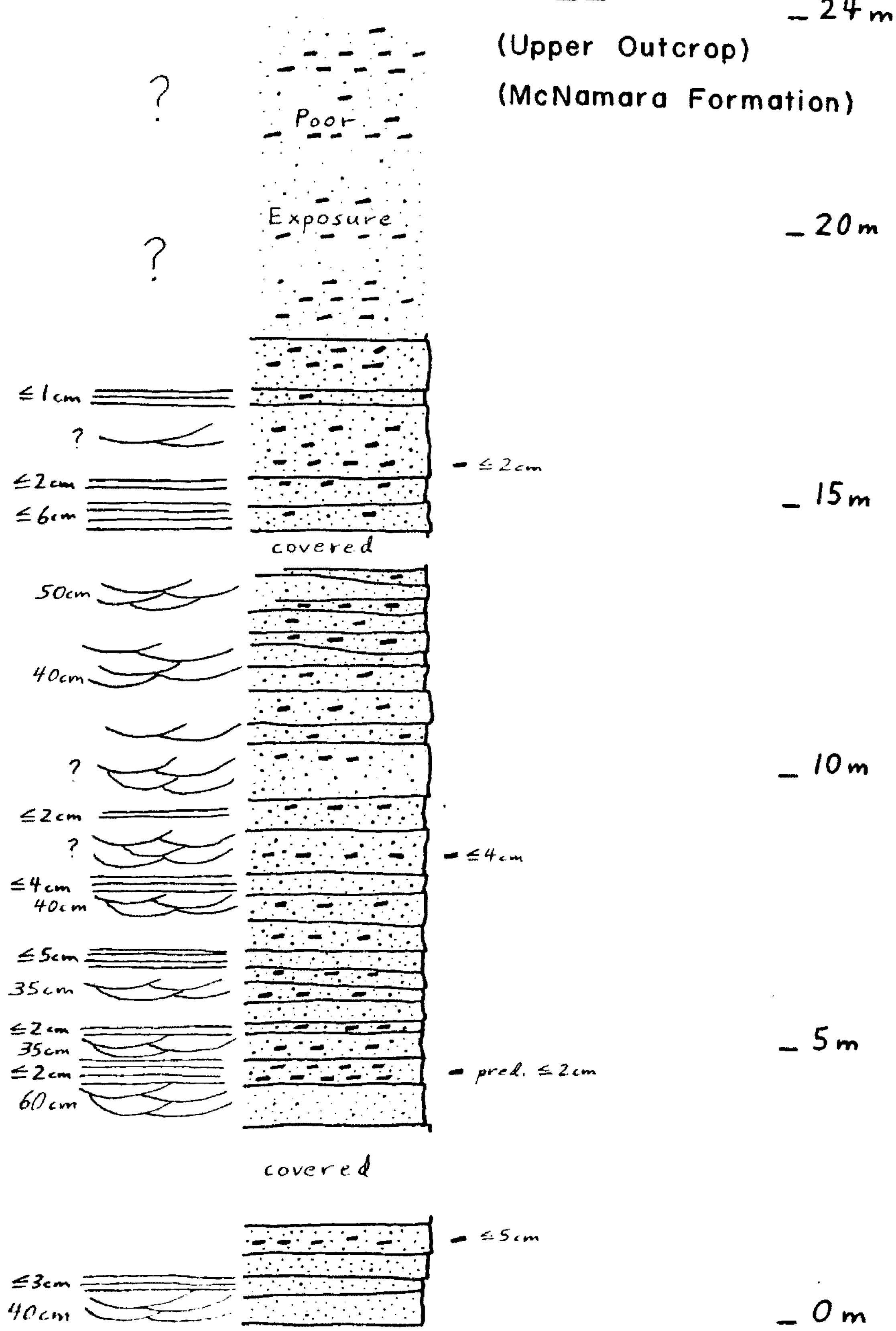


15cm
15cm
v. low ∠ 5cm
≤10cm
low ∠ 35cm
≤2cm
≤3cm
?
8cm
30cm
≤8cm
15cm
7cm
faint 8cm
faint ≤3cm
15cm
≤5mm
≤8mm
faint ≤6cm
≤2cm
faint
≤5cm
mnr ≤5cm
2-10cm
pbls ≤1.5cm
pbls ≤ 1.5cm
pbl lens 3cm thick, pbls ≤3cm
pbls ≤1cm
– 45m
4cm × >8m lens, pbls up to 3.5cm, ave. 1-2cm
-pred. matrix supported
pbls ≤1.5cm
pbls ≤1cm
pbls ≤2cm
= 8-18cm thick
pbls ≤1.5cm
pbl zones ≤3cm thick, pbls ≤1cm
– 40
pbls ≤1cm
pbls ≤1cm
mnr pbls ≤1cm
scour
mnr pbl zones ≤2cm thick, pbls ≤1cm
pbls ≤ 1cm
– 35
scour
= 6cm thick
= 8-12cm thick
pbl zone ≤10cm thick, pbls ≤8mm
30
5cm thick
scour
≤ 1x4cm -pbl zone ≤5cm thick, pbls ≤8mm
7x60cm lens w/ pbls up to 7mm
pbls ≤1cm
– 25


faint 10cm
v. low ∠ 6cm
≤ 5cm 20cm
≤ 1cm ≤ 3cm
≤ 4cm
10cm ≤ 5cm
20cm
20cm
?
?
?
≤ 5cm
15cm
?
6cm
20cm
5cm
7cm
7cm
10cm
30cm
?
≤ 8cm
10cm
≤ 4cm
≤ 3cm
≤ 5mm
? ≤ 5cm
3-6cm
6cm
15cm
≤ 8cm
8-20cm
≤ 2cm
?
4-10cm
≤ 2.5cm
= 6cm thick, lenticular bed
= 6cm thick, lenticular bed
– 70m
pbl zone 20-35cm thick X >3m lateral, pbls ≤ 2cm
scour
mnr pbls ≤ 1cm
pbl lens 5 x 60cm, pbls ≤ 1.5 cm
pbls ≤ 1.5cm
scour
pbls ≤ 1cm
– 65
pbls ≤ 8mm
pbl lens 8cm thick, pbls ≤ 1cm
pbls ≤ 1.5cm
pbl lens 15cm thick, pbls ≤ 2cm
pbl lens 15cm thick, pbls ≤ 1cm
5cm thick
abnt pbls ≤ 1.5cm
pbls ≤ 1.5cm
– 60
pbls ≤ 1cm
pbls in stringers 1.5 x 50cm, pbls ≤ 1cm, stringers horizontal
pbls ≤ 1cm
pbl lens ~20cm thick, pbls ≤ 1.5cm, lens >3m lateral
pbl lens 2 x 40cm, pbls ≤ 5mm
pbl lens 10cm thick, pbls ≤ 1cm
– 55
pbls ≤ 1.5cm
3 x 30cm pbl lens, pbls ≤ 2cm
pbls ≤ 1.5cm
pbls ≤ 1.5cm
pbl lens 3cm thick, pbls ≤ 2.5cm
pbl lenses ≤ 10cm thick, pbls up to 6.5cm, ave. 1-3cm
lens 3cm thick, pbls ≤ 3cm
– 50
pbls ≤ 1.5cm


mnr ≤ 2cm
10cm
≤ 3cm
10cm
15cm
mnr ≤ 3cm
= 8cm thick
pbl lens 15cm x 2m, pbls ≤ 6mm
— 90m
covered
mnr ≤ 8cm
covered
— 85
?
mnr pbls ≤ 1cm
covered
≤ 1cm
= 10 cm thick
covered
? faint
— 80
covered
faint ≤ 6cm
8-10cm
≤ 1cm
rare pbls ≤ 1cm
15cm x 7m lens
mnr pbls ≤ 5mm
≤ 1cm
? 8-10cm
= 8cm thick
pbl lens 15 x 150cm, pbls ≤ 2cm
— 75
? 1-8cm
mnr pbls ≤ 1.5 cm
▬ ≤ 2cm
≤ 1cm
faint 1-10cm
= 8cm thick
▬ 12 x 65 mm

FLINT CREEK HILL



APPENDIX III

GEOMETRY AND SCALE OF PARTED UNITS

Geometry and Scale of Parted Units

		Grain Size	Thickness	Geometry
Wise River				
Unit 1:		med-crs	50cm - 1.8 m	tabular to lenticular
Unit 2:	upper 1/2	med-crs with mnr cgl lenses	60cm - 1.8 m	tabular
	lower 1/2	med-crs with cgl lenses	5m	tabular
Unit 3:		silt	up to 30cm	tabular to lenticular
		fine	up to 45cm	tabular to lenticular
		med-crs	30cm - 1.8m	tabular to lenticular
Copper Creek				
Unit 1:		med-fine	up to 25cm	tabular to lenticular
		med-crs	40cm - 1.9m	tabular to lenticular
Unit 2:		med-crs with cgl lenses	1.1m - 3 m	tabular
Unit 3:		med-fine	up to 30cm	tabular to lenticular
		med-crs	40cm - 1.5m	tabular
Emerine Lookout				
Unit 1:		med-fine	up to 20cm	tabular to lenticular
		med-crs	12cm - 1.5m	tabular to mnr lenticular
Unit 2:		med-fine	up to 45cm	tabular to lenticular
		med-crs with cgl lenses	30cm - 2.1m	tabular
Unit 3:		med-fine	10cm - 45cm	tabular
		med-crs	25cm - 2.1m	tabular
Unit 4:		silt	3cm - 1.1m	tabular to lenticular
		med-fine	3cm - 1.1m	tabular to lenticular
		med-crs	15cm - 2.7m	tabular to lenticular
Flint Creek Hill				
Unit 1:		med-fine	up to 18cm	tabular to lenticular
		med-crs	20cm - 1.7m	tabular to mnr lenticular
Unit 2:		med-fine	up to 30cm	tabular to lenticular
		med-crs with cgl lenses	30cm - 1.4m	tabular to mnr lenticular
U-it 3:		med-fine	up to 30cm	tabular to lenticular
		med-crs	30cm - 1.2m	tabular

APPENDIX IV

MEMORABLE EXPERIENCES IN THE FIELD

Memorable Experiences in the Field

During my first quarter at the University of Montana (Fall, 1977), I was surprised to learn that most of the western third of the state contains sedimentary rocks (sandstones, mudstones, and limestones) which formed about a billion years ago, before land plants and animals appeared on earth. Having grown up in southeastern Georgia and studied geology there, I had seen my share of sedimentary rocks, but I had never encountered any nearly so old. At any rate, I became interested in these ancient sediments, and eventually wound up doing my master's thesis on the Bonner Formation, one of the sandstone units.

The field work began on Sunday, July 9, 1978. I wanted to find four or five different areas where I could look at significant thicknesses of the Bonner and see how the rocks compared from place to place. I had learned from Don Winston of two areas where good sections of Bonner Quartzite were exposed, and I spent the first day at one of these, Flint Creek Hill. During the early stages of the field work, as in many experiences, I was mainly trying to get a feel for what I was doing and figure out the best way to go about describing the section. After completing some brief, general descriptions and making what I would later find to be a fundamental error (I described part of the section as medium to coarse sand when actually it was medium to fine. I didn't have a sand-size card with me at the time). I went on to a nearby area (Cable Mountain) to look for another well-exposed section of Bonner. I had been to Cable Mountain previously and seen talus blocks of conglomeratic quartzite at the top of the mountain. Cable Mountain is accessible by a rocky road leading to the very top at over 7000 feet elevation. I spent the night on top in my van and woke to a sunny, clear morning and a fantastic view of the surrounding countryside. For people like myself, who really admire the earth's natural beauty, a fine feeling comes from being able to look out and see for 50 miles or more in every direction. I spent the entire day hiking down and back up the wooded mountainside looking for good rock exposure. I found none at all, but I did find how tiring it can be to hike straight up the steep side of a mountain climbing over 1000 vertical feet. Kind of gets you huffing and puffing.

The following weekend I returned with a friend to check out a different part of the Cable Mountain area. We camped in a valley west of the mountain Friday night, and were up with the sun (to my friend's displeasure) on Saturday. Still half asleep, we bounced our way along a rugged logging road in our small Chevy pickup. As we gained elevation, the road got worse rather than better, and within about 20 minutes we found ourselves securely stuck in one of the biggest and deepest mud puddles I've ever seen. At this point, I had to agree with my companion that maybe we shouldn't have gotton up so early. But it could have been worse. We just happened to have along one of those small, folding army shovels which I had bought (on sale) at the last minute before leaving Missoula the day before. I felt as if someone was trying to tell me that I had done the right thing in buying that shovel! So, we dug a small canal and drained most of the puddle. Then, while being eaten alive by mosquitos, we jacked-up each wheel and gradually filled in the entire puddle with cobbles from a nearby stream. After about two miserable hours, we managed to free ourselves. Then, deciding the road we were on wouldn't get us close enough to our destination, we headed back the way we had come. Later that day and the following day we scouted the area I was interested in, but again found no suitable place at which to measure a section. We did, however, see some nice country and also got caught in a hailstorm up on top of a high peak. We sat and watched the dark gray clouds moving eastward overhead, and before we knew it, thousands of marble-sized hailstones were hopping around on the ground. That was an unusual and rememberable July experience for a couple of south Georgians.

In mid-August I headed for the other known Bonner section, Wise River, to begin describing the rocks there. I arrived on a cool, overcast afternoon spattered with occasional rain. One neat thing about this area is the Elk Ranch just across the road from my section. There are about two dozen elk living within a large, fenced-in portion of the valley. These are just beautiful animals, and they look so at ease lying about the green pasture during the early morning. A few times I stopped along the road to look at and say hello to them up-close, but usually I would look down on them from high-up on the rocky slope across the road.

Even from way up there, the cluster of small, brown forms always seemed to add something special to the scene. So, here I was at Wise River, ready to get right into the nitty-gritty of the thesis. I started out measuring and describing the layered rock in 5-foot intervals For every interval, I would look carefully at the rock and write a long, detailed description in my field book. This was very time consuming and my notes were often repetitive. Even so, the change to a much easier and more efficient method of data collection did not come until I was nearly half finished with the field work. The mornings which greeted me at Wise River were commonly cool, with scattered, puffy white clouds crossing a sunny blue sky. Camped about 10 feet from the riverbank, I awoke each day to the constant sound of water rumbling across stones. After having breakfast and packing a lunch, I'd get my gear together, cross the small wooden bridge, and climb up the bouldery debris slope to the cliff base. Usually, before going to work, I'd sit and rest for a few minutes looking out over the valley and thinking to myself how prime it was that such an enjoyable experience was actually a part of going to school. I might see a few curious chipmunks and an occasional crow or jay throughout the day, but otherwise the mountainside was still and quiet (except for the river below). Almost every day at Wise River was sunny and clear, but on one afternoon the wind picked-up and the sky gradually darkened with thick, gray clouds. From my vantage point near the top of the section I felt the air growing cooler and watched as the sky threatened more and more of rain. The experience of the oncoming storm was surely exciting and maybe even a little scary. The whole environment seemed changed; windier, darker, and more hostile. The change made me think of how alone I was up on this mountainside and of how vulnerable I was in being alone. When the rain finally came, however, night had fallen and I was warm and dry in my van.

The end of August found me working at Flint Creek Hill. I had realized during the break between describing the Wise River section and starting at Flint Creek Hill that describing the rock in 10-foot rather than 5-foot intervals provided just as much detail and took less time. I was still writing a lot, trying to get good detail, and also drawing quite a few sketches. The weather was variable, with sunny days receiving much greater appreciation than the cool and rainy ones. On September 12 at Flint Creek Hill, I met the first snow of the season. One to two inches of fresh white powder coated trees and bushes and rocks. It made everything look really fine!

By early October I was describing the Emerine Lookout section. Talk about scenic! The lookout tower was perched on the mountain top at 8640 feet elevation, with a 360 degree panorama great for sunsets, sunrises, or just mid-day lunch breaks. Another real advantage was that you could drive all the way to the top. The comforts of the van were very welcome here since nights were often windy with temperatures below freezing. Clear and sunny weather prevailed, but I often worked under cool conditions because my section occurred within a shaded part of the mountainside. Being cold not only decreased the enjoyment of the work, but also reminded me that the field season would end soon. On October 27, I returned to Emerine Lookout from Missoula to find the small lake at the base of the section frozen and the mountainside dusted with about half an inch of fresh snow. I also found, to my disappointment, that the lookout tower had been dismantled and burned What a shame, I thought, to destroy such an excellent observation platform. But, at least I had been lucky enough to share some watchful moments with the tower before its disappearance. On that same evening I met a very small, but friendly owl. It was only about four inches tall, brown with thin white stripes on its breast and tail. While walking up a steep slope, I noticed the small bird watching me from a tree limb about 15 feet away. As I stopped and greeted him with a friendly "Hello, Mr. Owl", he merely swivelled his head around on his shoulders. The back of his head looked very much like the front, and after a few turns I couldn't really tell if he was looking toward me or away. Anyway, we just stood and observed each other for quite a while until finally he flew off. In search of some supper I presume. The next morning was cold with about half an inch of new snow. Even this thin coating made conditions too dangerous for measuring section, so I took a few photos and headed home, not to return until the following summer.

My first field stop during the summer of 1979 was back at Wise River. I needed to sketch a profile of the section, something that I should have done when first describing the rocks. By this time I had figured out that I could save a lot of time and writing by sketching the outcrop profile as I measured the section, and putting grain size, color, and sedimentary structure of the rock directly on the profile as symbols. I thought to myself, "Boy, I wish I'd been doing it this way all along." But then, you live and you learn, right? I caught my first Montana trout, a rather small one, during this visit to Wise River. Delicious! From there I headed to Flint Creek Hill to sketch outcrop profiles.

A week or so later I returned to Emerine Lookout. The work proceeded much faster now since I was putting most descriptive information on the profile sketch and thus not spending so much time writing notes in my field book. A few mornings were really spectacular. I remember waking-up on the mountaintop and stepping outside. The valleys below me were all filled with a sea of white clouds. In places, the higher dark hills and ridges climbed up through the white expanse. It's hard to describe the feelings I would experience on mornings such as this, but whatever it was it feld good, and these mornings always seemed to set the right mood for the rest of the day. During the several days I spent finishing this section, I experienced sunny and calm mornings, windy hailstorms on some afternoons, and a couple of good rainstorms with the added excitement of lightening and thunder. Among the rocks I often saw chip-munks, squirrels, and small, mouse-like creatures. These animals had probably not seen many humans, so they were not really afraid of me but just cautious. A few rather bold ones would run right past me. Of course, I couldn't have caught them even if I had wanted to. Many jays and a few hawks also lived on the mountainside. The jays would usually fly around from tree to tree talking to each other and making lots of noise. The hawks, on the other hand, would glide silently in big circles near the cliffs, hardly ever flapping their wings but constantly shifting their gaze back and forth. Watching these animals in their daily routine was very enjoyable.

On my first night at Copper Creek, the moon was full and a total lunar eclipse took place. I grew sleepy as I laid on the ground and watched the dark bite in the moon's edge slowly get bigger. As the night passed, I occasionally woke-up to see the bright arc that remained becoming progressively thinner. I don't recall ever seeing the moon disappear completely, but the show I did see was certainly satisfying. Under the nice weather I worked each day with no shirt on. The warm sunshine felt just great. I was also pleased to find a number of edible mushrooms in the woods surrounding the campground. Having been interested in such wild edibles for about a year, I was excited about finding a new variety. These were a type of Boletus which had light brown to tan caps with a sort of rough suede-like texture. The center of the cap was slightly darker than the outer parts, and the mushrooms were yellow on their undersides. Sliced and fried in butter, they turned-out to be very tasty. With the fine weather, the section description proceeded rapidly and in a couple of days I had finished. Now it was on to the less enjoyable work of interpreting the data and trying to figure out what it all means.